2024

INTERNATIONAL SOIL SCIENCE SYMPOSIUM on

SOIL SCIENCE & PLANT NUTRITION

(10th International Scientific Meeting)

13 – 14 December 2024

Samsun, Türkiye

BOOK OF PROCEEDINGS

Editors
Dr.Rıdvan KIZILKAYA
Dr.Coşkun GÜLSER
Dr.Orhan DENGİZ

Organized by
Federation of Eurasian Soil Science Societies
Erasmus Mundus Joint Master Degree in Soil Science (emiSS) Programme

With the support of the Erasmus+ Programme of the European Union

Cover design by FESSS

Editors:

Dr.Rıdvan Kızılkaya
Ondokuz Mayıs University, Faculty of Agriculture
Department of Soil Science and Plant Nutrition
55139 Samsun, Türkiye

Dr.Coşkun Gülser
Ondokuz Mayıs University, Faculty of Agriculture
Department of Soil Science and Plant Nutrition
55139 Samsun, Türkiye

Dr.Orhan Dengiz
Ondokuz Mayıs University, Faculty of Agriculture
Department of Soil Science and Plant Nutrition
55139 Samsun, Türkiye

ISBN 978-625-94343-3-9

This Book of Proceedings has been prepared from different papers sent to the symposium secretary only by making some changes in the format. Scientific committee regret for any language and/or aim-scope.

Publication date : 25 December 2024

Visit the Symposium web site at
http://www.fesss.org/

E-mail: symposium@fesss.org

COMMITTEES

Organizing Committee

CHAIR(S) OF ORGANIZING COMMITTEE

Dr.Rıdvan KIZILKAYA
Türkiye, Chair

Dr.Coskun GÜLSER
Türkiye, Vice-Chair

Dr.Orhan DENGİZ
Türkiye, Vice-Chair

MEMBER(S) OF ORGANIZING COMMITTEE

Dr.Agnieszka JÓZEFOWSKA
Poland

Dr.Ammar ALBALASMEH
Jordan

Dr.Andon ANDONOV
Bulgaria

Dr.Ivan MANOLOV
Bulgaria

Dr.Lesia KARPUK
Ukraine

Dr.Maira KUSSAINOVA,
Kazakhstan

Dr.Maja MANOJLOVİĆ
Serbia

Dr.Markéta MIHALIKOVA
Czech Republic

Dr.Michał GĄSIOREK
Poland

Dr.Svetlana SUSHKOVA
Russia

Dr.Tatiana MINKINA
Russia

Dr.Tomasz ZALESKI
Poland

Dr.Zhanna S. ALMANOVA
Kazakhstan

SECRETARY OF SYMPOSIUM

Res.Ass. Abdurrahman AY
Türkiye

Res.Ass. Salih DEMİRKAYA
Türkiye

Board of FESSS

MANAGEMENT

Dr.Ayten NAMLI
President of FESSS
President of Turkish Soil Science Society / Ankara University, Türkiye

Dr.Rıdvan KIZILKAYA
General Secretary of FESSS
Ondokuz Mayıs University, Türkiye

Dr.Coskun GÜLSER
Vice-President of FESSS
Ondokuz Mayıs University, Türkiye

Dr.Pavel KRASILNIKOV
Representative of Russian Soil Science Society / Lomonosov Moscow State University, Russia

Dr.Garib MAMMADOV
Representative of Azerbaijan Soil Science Society / Azerbaijan National Academy of Science, Azerbaijan

Dr.Erhan AKÇA
Representative of Turkish Soil Science Society / Adıyaman University, Türkiye

Dr.Beibut SULEIMENOV
Representative of Kazakhstan Soil Science Society / Kazakh Research Institute of Soil Science and Agrochemistry, Kazakhstan

Dr. Irina Carmen CALCIU
Representative of Romanian National Society of Soil Science / National Research-Development Institute for Soil Science, Agro-Chemistry and Environment, Romania

Dr.Boško GAJİĆ
President of Serbian Soil Soil Science Society / University of Belgrade, Serbia

Dr.Mihajlo MARKOVİĆ
President of Bosnia & Herzegovina Soil Science Society / University of Sarajevo, Bosnia & Herzegovina

Dr.Ermek BAIBAGYSHOV
President of Kyrgyzstan Soil Science Society / Naryn State University, Kyrgyzstan

Scientific Committee

Preface I

Dear Colleagues,

On behalf of the Federation of Eurasian Soil Science Societies (FESSS), it is with great pleasure that we welcome you to the "Soil Science and Plant Nutrition" (EURASIAN SOIL Symposium 2024). We are honored by your participation, which highlights the shared dedication of our community to advancing soil science and plant nutrition.

Continuing the tradition established in previous years, this symposium provides an exceptional platform for exchanging ideas, presenting groundbreaking research, and fostering collaboration among scientists, researchers, and practitioners. Under the enduring theme of "Soil Science and Plant Nutrition," this year's symposium will again explore applied research and innovative approaches to understanding soil's physical, chemical, and biological properties, plant nutrition, and fertility mechanisms across diverse ecosystems.

Spanning scales from molecular to global perspectives, the symposium embraces a multidisciplinary approach, encouraging the integration of diverse fields to tackle contemporary challenges. We remain committed to highlighting the latest advancements in soil science, innovative technologies, and fundamental concepts that drive progress in sustainable agriculture and environmental stewardship.

The EURASIAN SOIL Symposium 2024 provides a unique opportunity to deepen our understanding of soil systems, build valuable connections, and inspire new collaborations among participants from both academic and private sectors. It is our belief that the knowledge and ideas exchanged during this event will contribute significantly to the ongoing efforts to promote sustainable soil management and enhance plant productivity.

We are deeply grateful for your presence and contributions, which are the cornerstone of this symposium's success. We look forward to a program filled with insightful presentations, engaging discussions, and meaningful interactions that will enrich the soil science community and further its impact globally.

Once again, thank you for joining us. Let us make this symposium another memorable and impactful event for the advancement of soil science and plant nutrition.

Prof.Dr.Ayten Namlı
President, FESSS

Preface II

Dear Distinguished Colleagues and Esteemed Guests,

Good morning, and it is my great privilege to address you as the Secretary General of the Federation of Eurasian Soil Science Societies (FESSS) for the opening of the 10th Annual International Symposium on Soil Science and Plant Nutrition. I warmly welcome each one of you to this esteemed gathering, and I am delighted to see such a distinguished audience from across the globe.

First and foremost, I extend my heartfelt gratitude to our co-organizer, the Erasmus Mundus Joint Master Degree in Soil Science Programme (emiSS), and its dedicated Coordinator, Dr. Coşkun Gülser, for their ongoing collaboration and invaluable contributions. This year marks the continuation of a fruitful partnership between FESSS and emiSS, reinforcing our shared commitment to advancing soil science education and research.

I also wish to extend a special welcome to our esteemed colleagues from the University of Agriculture in Krakow, Poland, Agricultural University Plovdiv in Bulgaria, and the many other international participants who have joined us for this symposium. Your presence here is a testament to the power of global collaboration in addressing the pressing challenges in soil science and plant nutrition.

The theme of this year's symposium, "Soil Science and Plant Nutrition," remains at the forefront of efforts to understand the intricate relationships between soil health, plant productivity, and ecosystem sustainability. This symposium is designed to bridge theoretical research and practical applications, delving into the physical, chemical, and biological properties of soils and their interaction with plant nutrition and fertility mechanisms. Discussions will span a range of scales, from molecular-level processes to field-scale applications, emphasizing a multidisciplinary approach to solving complex environmental and agricultural challenges.

This event serves as a vital platform for showcasing recent advances in soil science, fostering dialogue among scientists, and building bridges between public and private sectors. It underscores the Federation's commitment to addressing critical issues through research and collaboration, with a focus on integrating innovative solutions and advancing fundamental knowledge.

Since its founding in 2012, the Federation of Eurasian Soil Science Societies has grown into a dynamic network of eight member countries, including Romania, Kyrgyzstan, Bosnia & Herzegovina, and Serbia. Together, we remain united in our mission to promote soil science, bridge the gap between research and policymaking, and raise public awareness about the critical role of soils in global sustainability.

I would like to extend my deepest thanks to the program steering committee for organizing an exceptional lineup of speakers, and my sincere appreciation to every speaker, moderator, and participant for their invaluable contributions. Your active engagement and insightful discussions will undoubtedly make this symposium a memorable and impactful event.

Wishing you all a productive and inspiring symposium filled with enriching interactions and collaborative opportunities.

Thank you.

Prof.Dr.Rıdvan Kızılkaya
Chair, Organization Committee

Preface III

Dear participants,

It is my great pleasure to join the 10th Annual International Soil Symposium on "Soil Science & Plant Nutrition" as a member of the organizing committee. This symposium has been collaboratively organized by the Federation of Eurasian Soil Science Societies (FESSS) and the ERASMUS MUNDUS Joint Master Degree in Soil Science (emiSS) programme. I would like to extend my sincere gratitude to FESSS and Prof. Dr. Rıdvan Kızılkaya, Chairman of the Symposium, for providing us with this valuable opportunity to represent the emiSS programme at this prestigious international event.
The emiSS programme, founded with the support of the Erasmus+ Programme of the European Union, is a collaborative initiative organized by a consortium of four universities: Ondokuz Mayıs University (OMU-Türkiye), University of Agriculture in Krakow (UAK-Poland), Agricultural University Plovdiv (AU-Bulgaria), and Jordan University of Science and Technology (JUST-Jordan). Since its establishment in 2019, the programme has aimed to address the growing need for skilled soil scientists through a comprehensive master's degree curriculum, focusing on soil science, soil management, soil fertility, soil ecosystems, and the development of intercultural and language skills.
To date, the emiSS programme has welcomed 73 international students from diverse regions around the globe, with 50 of them having successfully graduated. We are particularly proud that some emiSS students will be participating in this symposium, contributing to the scientific sessions with their oral presentations.
This symposium embodies the mission of fostering scientific exchange and collaboration. It serves as a platform for sharing novel approaches to soil science and plant nutrition, addressing contemporary challenges, and shaping future research directions. It also provides an exceptional opportunity for researchers, including young scientists, to enhance their knowledge and presentation skills while engaging with experts in the field. I am confident that the discussions and presentations during this symposium will enrich our collective understanding and inspire innovative ideas in soil science. Once again, I extend my heartfelt thanks to the organizing committee and all participants for their invaluable contributions and for sharing their expertise.
Wishing you a productive and insightful symposium experience.

Prof.Dr.Coşkun Gülser
emiSS Coordinator

International Symposium

EURASIANSOIL Symposium2024

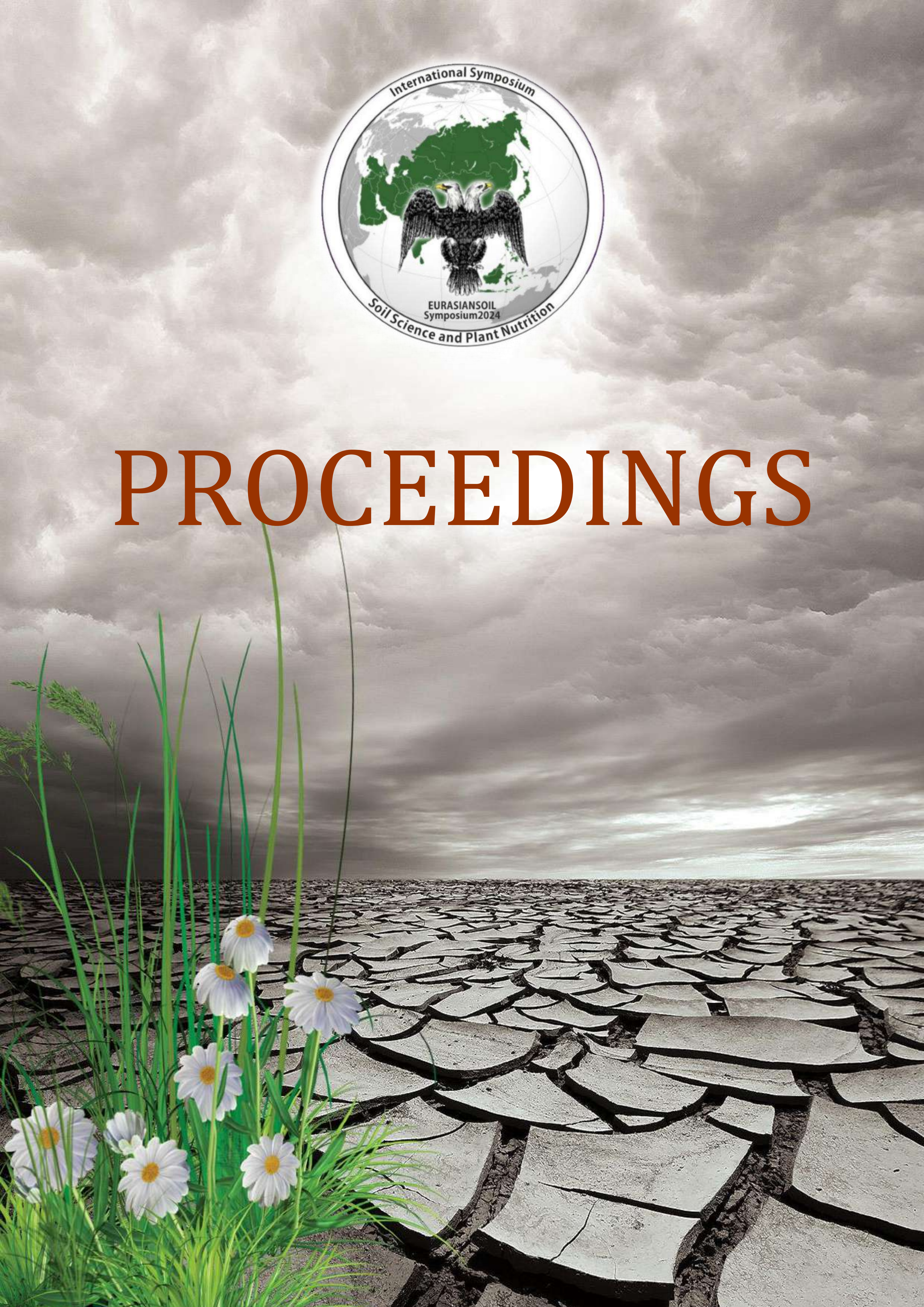
Soil Science and Plant Nutrition

CONTENTS

Contents

Contents

Contents


International Symposium
EURASIANSOIL
Symposium2024
Soil Science and Plant Nutrition
PROCEEDINGS

Urban soils organic carbon: A review

Abdelrahman TIEMA *, Michał GĄSIOREK
University of Agriculture in Krakow, Department of Soil Science and Soil Protection; Kraków, Poland

***Corresponding Author**

Abdelrahman TIEMA
abdelrahman.aamat@gmail.com

Abstract
Urban soils are increasingly recognized as crucial components of the global carbon cycle, yet their role in carbon sequestration remains underexplored. Urban areas, characterized by high levels of anthropogenic activity, offer significant potential to mitigate climate change through soil organic carbon (SOC) storage. However, urban soil faces unique challenges such as compaction, contamination, and soil sealing, which alter SOC dynamics. This paper synthesizes current knowledge on SOC in urban areas, focusing on its dynamics, characteristics, drivers of change, and strategies to enhance carbon sequestration. Key findings highlight the dual role of urban soils as both carbon sources and sinks, directly and indirectly, shaped by anthropogenic activities and urban management practices. Recommendations for improving SOC storage include long-term monitoring of urban SOC, sustainable land management practices, and integrating urban soils into climate policies.
Keywords: Soil Organic Carbon, SOM, Urban Soils, Urban Green Spaces

Introduction

Soils play a crucial role in the global carbon cycle, functioning as a major reservoir that stores more carbon than the atmosphere and terrestrial vegetation combined (Lefèvre et al., 2017). Soil organic carbon (SOC) is highly dynamic, and its dynamics are determined by the balance between carbon inputs and outputs (Blanco-Canqui et al., 2013; Smith et al., 2020). Inputs include aboveground and belowground plant and animal residues, while outputs involve losses through erosion, microbial and plant respiration, and leaching. Under natural conditions, soils can act as net carbon sinks by capturing atmospheric carbon dioxide (CO_2) through plant photosynthesis and organic matter decomposition (Smith et al., 2020). However, anthropogenic activities such as deforestation, intensive agriculture, urbanization, and land degradation disrupt this balance, accelerating SOC mineralization and contributing to greenhouse gas (GHG) emissions.

Despite an increasing number of regional studies on soil organic matter (SOM) stocks, research has primarily focused on agricultural and natural areas, often neglecting urban soils (Vasenev et al., 2013). The continuous increase in urbanization necessitates more urban soil surveys to assess their carbon storage potential (Vasenev et al., 2013; Vodyanitskii, 2015). Urbanization significantly alters regional soil carbon storage and composition patterns, making urban green spaces such as parks, gardens, and urban forests crucial for carbon sequestration (Chai et al., 2019; Lorenz and Rattan, 2009; Saier, 2009; Vasenev et al., 2013). These urban ecosystems face unique challenges, including compaction, contamination, and altered hydrology, which impact their SOM content and dynamics (Pouyat et al., 2006). This review aims to synthesize the current knowledge on SOC in urban green spaces, focusing on its role in carbon storage, factors influencing SOC dynamics, and strategies for enhancing SOM stocks in urban environments.

Urban SOC Compared to Non-Urban SOC

SOC Content

Several studies have been conducted to investigate the quality and quantity of soil organic carbon (SOC) in urban areas compared to non-urban areas. For instance, Vasenev et al. (2013) conducted a comparative study of SOC in urban and non-urban areas in Moscow, Russia, which revealed that SOC content in urban areas (3.3%) was significantly higher than in non-urban areas (2.7%). In contrast, Chien and Krumins (2022) with their meta-analysis of global natural and urban areas, comparing their carbon storage capacity under different climatic zones and vegetation types, revealed that natural habitats store significantly more SOC than urban areas. similarly, Chai et al. (2019) found that, compared to natural soils, the moisture content, total organic carbon, and total nitrogen in urban and rural soils of Beijing, China, significantly decreased. These contradictory findings regarding SOC levels in urban versus natural areas, underscore the need for a more comprehensive understanding of the urban soil dynamics and their role in the global C cycle and ecosystem services (Tratalos et al., 2007).

SOC Heterogenicity

SOC of urban areas is quite unique compared to agricultural and natural areas, as evidenced by its distinct characteristics (Vasenev et al., 2013; Vodyanitskii, 2015). One notable feature is the highly heterogeneous spatial pattern of SOC in urban areas compared to the gradual changes typically observed in agricultural and natural landscapes. SOM may decrease in some parts of a city and increase in other parts. At the soil profile level, urban soils can exhibit two SOC maximums, a phenomenon influenced by the unique dynamics of urban environments (Vasenev et al., 2013; Fig. 1). This heterogeneous SOC distribution results from abrupt anthropogenic activities such as soil movement during construction and settlement history. From the settlement history perspective, the term “Cultural layer,” was originally used in archaeological research to describe artifacts related to settlement history buried in soils. This term has been adopted later in urban soil studies to refer to anthropogenic influences, including buried non-urban horizons, coal, and wooden remains found in specific soil layers.

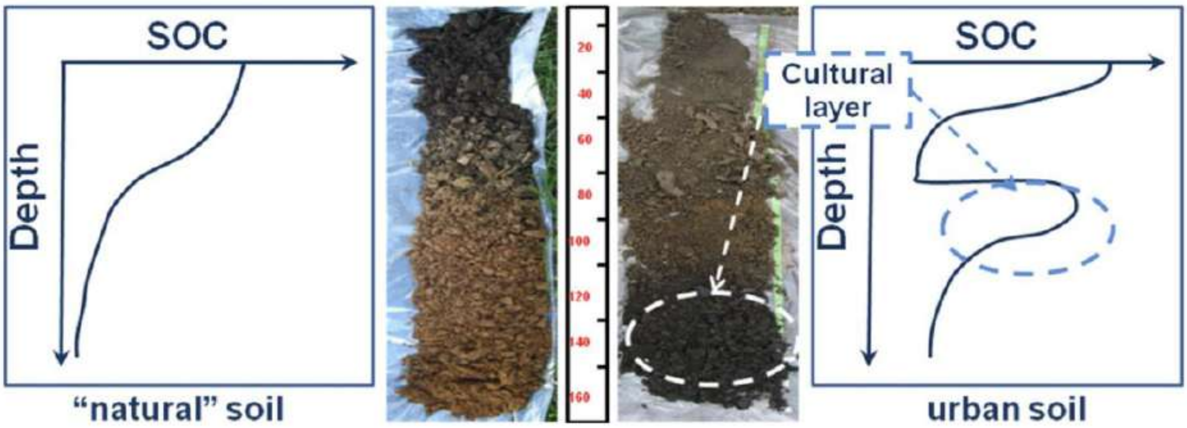


Figure 1. Sketch of SOC profile distribution for urban and natural soils (Vodyanitskii, 2015).

Urban SOC Dynamics and Factors

Contrary to natural soils, pedogenesis, properties, and functions, of urban soils are primarily influenced by anthropogenic origins and activities (Lehmann and Stahr, 2007). Anthropogenic activities influence soils through both direct and indirect mechanisms (Lorenz and Rattan, 2009). Direct influences involve alterations in the biological, chemical, and physical properties of urban soils. In contrast, indirect influences arise from broader environmental changes, such as regional and global atmospheric climate changes (e.g., urban heat island and pollution island effects), atmospheric deposition of pollutants, and the introduction of exotic and invasive plant and animal species. Together, these factors, alongside soil parent material and land use, collectively determine the properties and functions of urban soils.

Urban Carbon Accumulating Factors:

Generally speaking, Urban soils organic carbon accumulation is promoted by the input of anthropogenic organic pollutants, slowed down mineralization of organic material under the influence of chemical contaminations, vegetation increased productivity in urban areas under the influence of high temperature, high CO2 atmospheric content, and maintenance of urban green spaces (i.e., fertilization and irrigation) (Vodyanitskii, 2015).

Anthropogenic Pollutants

Organic pollutants in urban areas, such as products of incomplete combustion of solid and liquid fuels, are often carried as fine aerial particles or soot, particularly in industrial zones. These, along with food waste, sewage sediments, and other common anthropogenic organic waste materials, contribute to soil carbon input, along with plant residues and other organic waste material in urban green spaces (Vodyanitskii, 2015). Mao et al. (2014), in their study on the spatial distribution of pH and organic matter in urban soils in Xuzhou, China, observed that soil organic matter (SOM) content varied widely, ranging from 3.51 g/kg to 17.12 g/kg with the central urban area characterized by low pH and high soil organic carbon (SOC). They concluded that the elevated concentration of SOC in the central urban area (Fig. 2) might be attributed to the high abundance of anthropogenic organic particles in the central urban area. Similarly, Vasenev et al. (2013), in a comparative study of SOC in urban, natural, and agricultural areas in Moscow, Russia, demonstrated that urban areas had significantly higher SOC content than non-urban areas (3.3% compared to 2.7%). This difference was attributed to the so-called "cultural layer," a phenomenon resulting from human residential activity and settlement history.

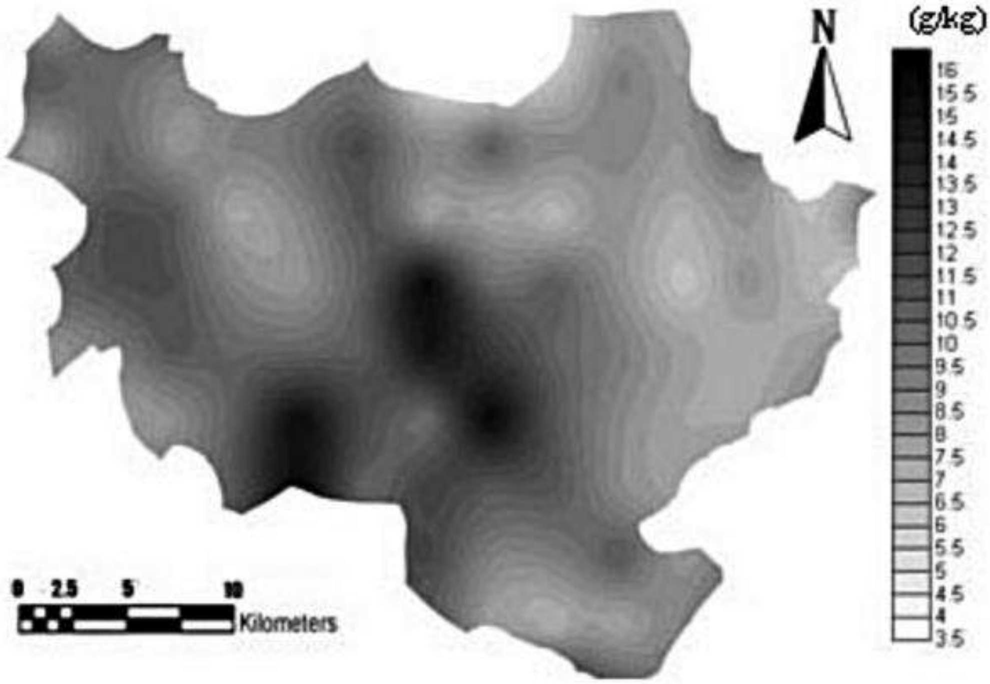


Figure 2. Spatial distribution of SOM in Xuzhou, China (Mao et al., 2014).

In addition to carbon pollutants, chemical contamination in urban areas may negatively impact the mineralization rate of organic residues, thereby increasing the carbon content in urban soils (Vodyanitskii, 2015). From a sustainable resource management prospective, utilization of recovered resources available in urban area as soil amendments, such as compost, biosolids, and harvested nutrients from wastewater, could improve the fertility and ecosystem function of urban soils (Kumar and Hundal, 2016). Malone et al. (2023) with their meta-analysis concluded that applications of compost, biochar, and biosolids as organic matter amendments led to an average increase of 3.6 units of urban SOM %. Compost and biochar improved SOM% the most, by 3.1 and 6.5 units of SOM%, respectively. Biosolids resulted in the smallest increase in SOM% but had greater nutrient benefits than other amendments.

Increased Vegetation Mass and Productivity

Increased vegetation mass and productivity, driven by high temperatures, elevated CO2 concentrations in the air, and human interventions such as fertilization and irrigation, is another significant factor contributing to elevated SOC levels in urban areas (Vodyanitskii, 2015; Zhang et al 2022). Zhang et al. (2022), in their study on SOC changes in suburban and urban areas of Beijing and 21 other highly urbanized cities across China over the past three decades, found that SOC in topsoils decreased by 17.2% in suburban areas but increased by 104.4% in urban areas. These changes in SOC were positively correlated with increases in vegetation coverage and productivity. In addition to vegetation mass and productivity, the composition of vegetation species plays a critical role. Setälä et al. (2016) examined the ability of three common functional plant groups (evergreen trees, deciduous trees, and grass/lawn) to influence soil properties in urban parks of different ages (10, 50, and >100 years) under cold climatic conditions in Finland. Their findings suggest that plant-soil interactions in urban parks, despite being constructed environments, are strikingly similar to those in natural forests. Soils under evergreen trees exhibited the lowest pH and the highest levels of organic matter, total carbon, and total nitrogen, likely due to the recalcitrant nature of their litter and root exudates, which lower soil pH and enhance organic matter content compared to lawns.

Urban Carbon Depleting Factors

Soil Sealing, and Compaction

Soil compaction and sealing significantly impact soil organic carbon (SOC) levels (Lorenz and Lal, 2009). Compaction, often resulting from heavy machinery use, increases soil bulk density and reduces porosity, leading to decreased water infiltration and root penetration (Shaheb et al., 2021). This creates an environment with limited oxygen, hindering microbial activity essential for organic matter decomposition and SOC stabilization. Pulido-Moncada et al. (2019) with their four-year soil compaction study in Denmark demonstrated that wheel loads of 8 Mg with 4–5 multiple passes significantly increased soil bulk density and altered subsoil structural quality, adversely affecting SOC dynamics. Soil sealing, through the construction of impervious surfaces like roads and buildings, further disrupts the carbon cycle by halting organic matter inputs from vegetation and microbial activity (De Laurentiis et al., 2024). Sealed soils are deprived of oxygen and water infiltration, leading to a decline in microbial activity and organic matter decomposition. Additionally, the removal of vegetation during construction reduces primary sources of organic carbon input, such as leaf litter and root exudates, exacerbating SOC depletion.

Reduced Vegetation Cover

Urban areas often experience a reduction in vegetation cover due to competing demands for space. While urban green spaces contribute positively to SOC, the limited extent of these areas compared to impervious surfaces diminishes the overall carbon storage potential (Setälä et al., 2016). Furthermore, fragmented and poorly managed green spaces may have reduced vegetation density and diversity, which negatively impacts carbon inputs through litter fall and root biomass.

Increased Soil Contamination

Urban soils are often contaminated with heavy metals and other pollutants due to industrial activities, emissions, and improper waste disposal (Vodyanitskii, 2015). These contaminants can inhibit microbial activity and disrupt the decomposition of organic matter, slowing the formation of stable SOC compounds. Meng et al. (2023) with their urban soils heavy metal study in Beijing, China, revealed significant heavy metal accumulation in urban soils, attributed to industrial emissions and traffic pollutants. Similarly, Adedeji et al. (2018) found elevated levels of lead and cadmium in urban soils near industrial zones in Lagos, Nigeria, impacting microbial activity and SOC dynamics. Contamination also alters soil chemistry, such as pH and nutrient availability, further affecting SOM dynamics (Vodyanitskii, 2015). In Xuzhou, China, Mao et al (2014) found that that low pH conditions in contaminated urban soils were attributed to reduced soil organic matter (SOM) levels. Similarly, Jarosławiecka et al. (2022) study of urban soil HMs from two contaminated sites (i.e., Piekary Śląskie and Bukowno) in Poland have shown that nutrient imbalances caused by chemical pollutants alter microbial communities, disrupt carbon cycling, and decrease soil organic carbon (SOC) stabilization.

Accelerated Mineralization from Urban Heat Island Effects

The urban heat island (UHI) effect, characterized by elevated temperatures in urban areas compared to their rural surroundings, accelerates organic matter decomposition (Churkina, 2016). Higher soil temperatures stimulate microbial activity, leading to increased mineralization of SOC and higher CO_2 emissions. For example, a study in Phoenix, Arizona by Chow et al. (2012), demonstrated that urban soil temperatures were consistently 3–5°C higher than surrounding rural areas, significantly enhancing microbial respiration rates and SOC mineralization.

Poor Organic Waste Management

Inefficient organic waste management in urban areas can lead to the loss of potential organic carbon inputs to soils (Kumar and Hundal, 2016). For instance, green waste from parks and gardens is often incinerated or sent to landfills instead of being composted and returned to urban soils. This practice deprives urban soils of an important source of organic matter that could otherwise enhance SOC stocks.

Loss of Historical Carbon Pools and Land Cover Changes

Urbanization often leads to the destruction of natural and agricultural soils with historically accumulated carbon pools (Lorenz and Lal, 2009). These soils, once disrupted, release stored carbon into the atmosphere due to exposure to oxygen and microbial decomposition. Urban land-use change thus transitions soils from carbon sinks to sources, further contributing to global carbon emissions. Additionally, the removal of vegetation during construction reduces the primary source of organic carbon input, such as leaf litter and root exudates, further exacerbating SOC depletion.

Conclusion

The synthesis of existing studies reveals that urban soils are vital reservoirs of SOC with significant potential to mitigate climate change. However, urban soils face numerous challenges, including soil sealing, compaction, contamination, and reduced vegetation cover, which hinder their ability to function as effective carbon sinks. To address these challenges, efforts should focus on long-term monitoring urban SOC to further understand the complex effects of anthropogenic activities on urban soils and implementation of sustainable urban land management practices, including the utilization of recovered resources available in urban area as soil amendments, which is a sustainable waste management method that can significantly enhance SOC levels, improving soil quality, and expanding vegetation cover and diversifying plant species in urban areas which can further boost carbon inputs through organic matter deposition and root biomass. Additionally, integrating urban soils into global carbon management frameworks and climate policies is essential to fully harness their potential for carbon sequestration.

References

Adedeji, O.H., Olayinka, O.O., Tope-Ajayi, O.O., Awosika, D.A., 2018. Spatial Distribution and Health Risk Assessment of Heavy Metals in Urban Parks and Gardens Soils in Lagos State, Nigeria. Journal of Agricultural Science and Environment, 18(1), 16-35.

Bekier, J., Jamroz, E., Walenczak-Bekier, K., Uściła, M., 2023. Soil organic matter composition in urban soils: a study of Wrocław agglomeration, SW Poland. Sustainability, 15(3), 2277.

Blanco-Canqui, H., Shapiro, C.A., Wortmann, C.S., Drijber, R.A., Mamo, M., Shaver, T.M., Ferguson, R.B., 2013. Soil organic carbon: The value to soil properties. Journal of Soil and Water Conservation, 68(5), 129A-134A.

Chai, L., Huang, M., Fan, H., Wang, J., Jiang, D., Zhang, M., Huang, Y., 2019. Urbanization altered regional soil organic matter quantity and quality: Insight from excitation emission matrix (EEM) and parallel factor analysis (PARAFAC). Chemosphere, 220, 249-258.

Chien, S.C., Krumins, J.A., 2022. Natural versus urban global soil organic carbon stocks: A meta-analysis. Science of The Total Environment, 807, 150999.

Chow, W.T., Brennan, D., Brazel, A.J., 2012. Urban heat island research in Phoenix, Arizona: Theoretical contributions and policy applications. Bulletin of the American Meteorological Society, 93(4), 517-530.

Churkina, G., 2016. The role of urbanization in the global carbon cycle. Frontiers in Ecology and Evolution, 3, 144.

De Laurentiis, V., Maier, S., Horn, R., Uusitalo, V., Hiederer, R., Chéron-Bessou, C., Sala, S., 2024. Soil organic carbon as an indicator of land use impacts in life cycle assessment. The International Journal of Life Cycle Assessment, 1-19.

Jarosławiecka, A.K., Piotrowska-Seget, Z., 2022. The effect of heavy metals on microbial communities in industrial soil in the area of Piekary Śląskie and Bukowno (Poland). Microbiology Research, 13(3), 626-642.

Kumar, K., Hundal, L.S., 2016. Soil in the city: Sustainably improving urban soils. Journal of Environ Qual, 45(1), 2-8.

Lefèvre, C., Rekik, F., Alcantara, V., Wiese, L., 2017. Soil organic carbon: the hidden potential (pp. ix+-77).

Lehmann, A., Stahr, K., 2007. Nature and significance of anthropogenic urban soils. Journal of Soils and Sediments, 7, 247-260.

Lorenz, K., Lal, R., 2009. Biogeochemical C and N cycles in urban soils. Environment international, 35(1), 1-8.

Malone, Z., Berhe, A.A., Ryals, R., 2023. Impacts of organic matter amendments on urban soil carbon and soil quality: A meta-analysis. Journal of Cleaner Production, 419, 138148.

Mao, Y., Sang, S., Liu, S., Jia, J., 2014. Spatial distribution of pH and organic matter in urban soils and its implications on site-specific land uses in Xuzhou, China. Comptes rendus biologies, 337(5), 332-337.

Meng, D., Shao, Y., Luo, M., Liu, Z., Xu, D., Ma, L., 2023. Risk Assessment and source analysis of soil heavy metal (oid) s pollution in Beijing, China. Water, Air, & Soil Pollution, 234(9), 574.

Pouyat, R.V., Yesilonis, I.D., Nowak, D.J., 2006. Carbon storage by urban soils in the United States. Journal of Environmental Quality, 35(4), 1566-1575.

Pulido-Moncada, M., Munkholm, L.J., Schjønning, P., 2019. Wheel load, repeated wheeling, and traction effects on subsoil compaction in northern Europe. Soil and Tillage Research, 186, 300-309.

Saier Jr, M.H., 2008. Are megacities sustainable? Water, air and soil pollution, 191(1-4), 1.

Setälä, H.M., Francini, G., Allen, J.A., Hui, N., Jumpponen, A., Kotze, D.J., 2016. Vegetation type and age drive changes in soil properties, nitrogen, and carbon sequestration in urban parks under cold climate. Frontiers in Ecology and Evolution, 4, 93.

Shaheb, M.R., Venkatesh, R., Shearer, S.A., 2021. A review on the effect of soil compaction and its management for sustainable crop production. Journal of Biosystems Engineering, 1-23.

Tratalos, J., Fuller, R.A., Warren, P.H., Davies, R.G., Gaston, K.J., 2007. Urban form, biodiversity potential and ecosystem services. Landscape and urban planning, 83(4), 308-317.

Vasenev, V.I., Stoorvogel, J.J., Vasenev, I.I., 2013. Urban soil organic carbon and its spatial heterogeneity in comparison with natural and agricultural areas in the Moscow region. Catena, 107, 96-102.

Vodyanitskii, Y.N., 2015. Organic matter of urban soils: A review. Eurasian Soil Science, 48, 802-811.

Zhang, Z., Gao, X., Zhang, S., Gao, H., Huang, J., Sun, S., Xia, X. 2022. Urban development enhances soil organic carbon storage through increasing urban vegetation. Journal of Environmental Management, 312, 114922.

Effectiveness of leaching and drainage systems in salinity control on reclaimed soils: A review

Abdullah BALCI *, Tomasz ZALESKI

University of Agriculture in Krakow, Department of Soil Science and Soil Protection; Kraków, Poland

***Corresponding Author**

Abdullah BALCI

abdullahblcci@gmail.com

Abstract

Salinity control is a critical challenge for agricultural productivity in reclaimed soils, particularly in arid and semi-arid regions. Leaching and drainage systems are widely adopted strategies for mitigating soil salinity. Leaching involves the application of excess water to dissolve and move salts beyond the root zone, while drainage systems facilitate the removal of saline water to prevent salt accumulation. This review examines the effectiveness of these approaches, emphasizing their mechanisms, influencing factors, and recent technological advancements. Although both strategies are effective under proper management, challenges such as water scarcity, soil heterogeneity, and environmental impacts necessitate integrated and sustainable approaches. This paper explores innovative solutions, including precision irrigation, controlled drainage, and the use of treated wastewater, to enhance the efficiency and sustainability of salinity control practices.

Keywords: Soil salinity management, leaching techniques, Drainage systems, Reclaimed soils, Sustainable agriculture

Introduction

Soil salinity is a pressing global issue that poses significant threats to agricultural productivity, particularly in reclaimed lands. Salinization is commonly caused by natural processes such as weathering of parent material and evaporation, but human-induced factors, including improper irrigation practices, inadequate drainage, and overuse of saline water, intensify the problem. Reclaimed soils, often located in arid and semi-arid regions, are especially vulnerable to salinity due to high evaporation rates and poor water management. It is estimated that over 20% of irrigated lands worldwide are affected by salinization, threatening food security and the sustainability of agricultural practices (Qadir et al., 2014). Leaching and drainage systems have long been recognized as essential tools for managing soil salinity. Leaching involves applying excess water to dissolve and flush salts from the root zone, while drainage systems are designed to remove excess water, thereby preventing salt accumulation in the soil. Both strategies are critical for improving soil health and maintaining agricultural productivity in saline-prone areas. However, their effectiveness depends on several factors, including soil type, irrigation water quality, and system design. While traditional methods have proven effective in many contexts, challenges such as water scarcity, environmental impacts, and economic constraints require the adoption of innovative and sustainable approaches.

Recent advancements in technology, such as precision irrigation, automated drainage systems, and IoT-based monitoring tools, offer new opportunities to optimize the efficiency of leaching and drainage practices. These advancements not only address the limitations of conventional methods but also enable the development of integrated solutions tailored to specific environmental and agricultural conditions.

This paper provides a comprehensive review of the effectiveness of leaching and drainage systems in controlling salinity on reclaimed soils. It explores the underlying mechanisms, evaluates the factors influencing their success, and discusses the potential of modern technologies and sustainable practices to enhance their efficiency. The review aims to offer insights into practical and scalable solutions for managing soil salinity in reclaimed lands, ensuring their long-term viability for agriculture and ecosystem health.

Mechanisms of Leaching and Drainage

Leaching

Leaching is the process of applying excess water to the soil to dissolve and transport salts away from the root zone. The water percolates through the soil profile, carrying soluble salts down to deeper layers or into the drainage system. The efficiency of leaching depends on factors such as the soil's texture, permeability, and the quality of the water used. For instance, sandy soils, which have higher infiltration rates, allow faster salt movement compared to clayey soils that retain water and impede salt leaching (Ghassemi et al., 1995).

The leaching requirement (LR), a critical parameter in this process, defines the minimum water volume needed to reduce soil salinity to a level suitable for crop growth. It is influenced by the electrical conductivity of the irrigation water and the tolerance of the crop being cultivated. Effective leaching requires uniform water application, usually through methods like flood irrigation or sprinklers (Rhoades et al., 1992).

Drainage Systems

Drainage systems complement leaching by removing excess water from the soil profile, preventing waterlogging and salt accumulation near the surface. There are two primary types of drainage systems:

Surface Drainage: Removes water from the soil surface using ditches and channels. It is effective for managing temporary waterlogging caused by heavy rains or irrigation.

Subsurface Drainage: Utilizes perforated pipes or tile drains installed beneath the soil surface to lower the water table and remove salts from deeper soil layers. Subsurface drainage is particularly effective in areas with saline groundwater, as it prevents the upward movement of salts due to capillary action (Skaggs et al., 2012).

These systems function synergistically to improve soil conditions. Leaching reduces salt concentration in the root zone, while drainage prevents the re-accumulation of salts and ensures the sustainability of the reclamation process. However, the effectiveness of these systems depends on proper design, such as the spacing and depth of drainage channels, as well as the availability of adequate water resources for leaching (Corwin et al., 2007).

Leaching and drainage work in tandem. While leaching moves salts down the soil profile, drainage systems ensure their removal from the root zone and prevent reaccumulation due to capillary rise. Without effective drainage, leaching water may cause waterlogging and further salinization.

These mechanisms provide a robust framework for managing soil salinity, especially when combined with modern technologies like IoT sensors for real-time monitoring and adaptive management (Zhao et al., 2021).

By integrating these mechanisms, reclaimed soils can be maintained at salinity levels conducive to crop growth, ensuring long-term agricultural productivity. However, their success requires careful management to avoid negative environmental impacts, such as saline drainage water contaminating surrounding ecosystems.

Factors Influencing Effectiveness

Soil Properties: Permeability, texture, and structure significantly affect water infiltration and salt movement. Sandy soils are more responsive to leaching compared to clayey soils (Ghassemi et al., 1995). Low-permeability soils, such as clays and silts, retain water for longer periods but may experience slow drainage, leading to salt buildup in the root zone unless effective drainage systems are implemented (Sharma & Minhas, 2005).

Coarse-textured soils, such as sandy soils, have larger pores, allowing for faster water infiltration and quicker leaching of salts. This makes leaching more efficient in sandy soils, as water can quickly move through the soil profile, flushing out soluble salts (Richards, 1954). In contrast, fine-textured soils, such as clayey soils, have smaller pores and slower infiltration rates. As a result, leaching in these soils is less efficient, as water moves more slowly and may not reach deeper layers where salts accumulate (Hoffman, 1980).

Irrigation Water Quality: High-salinity irrigation water can reduce leaching efficiency, necessitating freshwater or blended water sources (Corwin et al., 2007).

Drainage Design: The spacing, depth, and layout of drainage systems impact their ability to manage salinity. Advanced design tools like DrainMod enhance their efficiency (Skaggs et al., 2012).

Technological Advancements

Precision Monitoring

IoT-based sensors monitor soil salinity, moisture, and water table levels in real-time, enabling targeted leaching and drainage interventions (Zhao et al., 2021).

Controlled Drainage

Controlled drainage systems regulate water tables dynamically to balance salinity management and water conservation, reducing nutrient losses and improving yields (Evans et al., 1995).

Water Reuse

Treated wastewater offers a sustainable water source for leaching, minimizing freshwater dependency and providing additional nutrients to crops (Ritzema et al., 2008).

Challenges and Limitations

Water Scarcity: Leaching requires significant water volumes, which may not be available in arid regions.

Environmental Impacts: Inefficient drainage can lead to downstream contamination with salts and agrochemicals (Ghassemi et al., 1995).

Economic Constraints: High installation and maintenance costs limit the adoption of advanced systems, particularly in developing regions.

Case Studies

A study conducted in the Nile Delta, Egypt where old drainage systems were rehabilitated, and new tile drains were installed. Soil salinity levels dropped by 50% within five years, with a noticeable increase in agricultural output. The project emphasized participatory management, involving farmers in maintenance. Abdel-Fattah, (2012)

A study conducted in the Murray-Darling Basin, Australia that Precision leaching and subsurface drainage systems were installed, combined with real-time monitoring technologies. Salinity levels were reduced significantly, and crop yields improved. Real-time monitoring allowed for targeted interventions, minimizing water use and environmental impacts. Ghassemi et al., (1995)

A study by Ritzema et al., (2008) where Subsurface drainage systems combined with leaching were introduced. The intervention led to a significant reduction in soil salinity and a 20-30% increase in crop productivity. Farmers reported better soil tilth and reduced waterlogging.

Conclusion

Leaching and drainage systems remain essential tools for controlling salinity on reclaimed soils. While traditional methods are effective, their limitations necessitate the adoption of advanced technologies and integrated approaches. Addressing challenges such as water scarcity and environmental impacts is critical for ensuring the sustainability of these practices. Future research should focus on cost-effective and scalable innovations to support global salinity management efforts.

Future research should focus on:

- Combining leaching and drainage with agronomic practices such as crop rotation, the use of salt-tolerant crops, and soil amendments can improve overall salinity management.
- Utilizing treated wastewater, blending saline with freshwater, and implementing precision irrigation techniques can mitigate water scarcity challenges.
- Tailoring drainage systems to specific field conditions, including the use of advanced materials and dynamic designs, can improve performance while minimizing environmental impacts.
- Combining real-time monitoring systems for soil and water salinity allows for timely interventions and minimizes resource wastage.
- Developing safe disposal methods for saline drainage water and exploring reuse options, such as aquaculture or saline agriculture, can reduce ecological harm.

References

Corwin, D.L., Lesch, S.M., Oster, J. D., Kaffka, S.R., 2007. Monitoring management-induced spatio-temporal changes in soil salinity using electromagnetic induction techniques. Geoderma, 139(1-2), 237-249.

Evans, R.O., Skaggs, R.W., Gilliam, J.W., 1995. Controlled versus conventional drainage effects on water quality. Journal of Irrigation and Drainage Engineering, 121(4), 271-276.

Ghassemi, F., Jakeman, A.J., Nix, H.A., 1995. Salinization of land and water resources: Human causes, extent, management, and case studies. UNESCO.
Qadir, M., Qureshi, R.H., Sato, T., 2007. Reclamation of saline-sodic soils: Biological and economic considerations. Soil Use and Management, 23(1), 2-9.
Rhoades, J.D., Kandiah, A., Mashali, A.M., 1992. The use of saline waters for crop production. FAO Irrigation and Drainage Paper 48.
Ritzema, H.P., Satyanarayana, T.V., Raman, S., Boonstra, J., 2008. Subsurface drainage to combat waterlogging and salinity in irrigated lands in India: Lessons learned in farmers' fields. Agricultural Water Management, 95(3), 179-189.
Skaggs, R.W., Brevé, M.A., Gilliam, J.W., 2012. Drainage water management for water quality improvement. Journal of Soil and Water Conservation, 44(3), 568-573.
Zhao, J., Liu, H., Zhang, H., 2021. IoT-based sensor networks for soil monitoring and salinity control. Computers and Electronics in Agriculture, 182, 105967.
Zhang, X., Huang, G., Zha, J., 2020. Enhancing water use efficiency for crop production by optimizing irrigation and drainage management under saline conditions. Agricultural Water Management, 234, 106154.
Hoffman, G.J., 1980. Guidelines for the reclamation of salt-affected soils. California Agriculture, 34(4), 10–12.
Richards, L.A., 1954. Diagnosis and improvement of saline and alkali soils. USDA Agriculture Handbook 60.
Sharma, D.P., Minhas, P.S., 2005. Strategies for managing saline/alkali waters for sustainable agricultural production. Agricultural Water Management, 78(1–2), 136–151.
Abdel-Fattah, M.K., 2012. Role of gypsum and compost in reclaiming saline-sodic soils. Land Degradation & Development, 23(2), 130-137.

Assessing the effects of windthrow and regeneration strategies on soil ecology: A comprehensive review

Adil ZIA *, Agnieszka JÓZEFOWSKA
University of Agriculture in Krakow, Department of Soil Science and Soil Protection; Kraków, Poland

***Corresponding Author**

Adil ZIA
aadil.zia00@gmail.com

Abstract
Windthrow events which are capable of breaking many trees off and uprooting them causing a major disruption to the forests. Soil fauna, especially soil annelids are particularly affected by the post-disturbance generation approaches aimed at recovering these altered forests, Soil annelids are important contributors to soil health and nutrient cycling, mediating important ecosystem processes like decomposition, nutrient mineralization, and soil structure. This review reflects the current knowledge on the effects of regeneration strategies, such as natural regeneration and artificial reforestation, on soil annelid communities in windthrow sites. It also explores how factors like plant species composition, litter quality, and soil disturbance mediate the abundance, diversity, and activity of soil annelids. Additionally, it also highlights how soil annelids respond to different forest regeneration strategies and their contribution to healthy soil and resilient ecosystems.

Keywords: Ecosystem Restoration, Forest Regeneration, Post-disturbance, Soil annelids

Introduction

Natural disturbance is one of the classic problems in forest ecosystems (Shorohova et al., 2023). Windthrow which is defined as the uprooting or breaking of trees due to wind is the largest forest disturbance in temperate forests. It is the process that affects forest dynamics and biodiversity. Also, in Central Europe windstorms are considered one of the most severe natural disasters (Fischer et al., 2002), causing both small clearances and extensive large-scale destruction, covering hundreds of trees (Bouget and Duelli, 2004). Regeneration of forests after wind damage through two paths may be taken: natural regrowth and artificial rehabilitation. Natural regrowth relies on the inherent restoration systems of a forest, including seed goodnesses (seed banks), surviving (or sometimes surviving) seedlings, and natural succession processes (Kramer et al., 2014). Such a method often generates mixed-aged stands. On the other hand, artificial rehabilitation involves intervention by human effort to set the tree species by planting certain species in so produce even-aged stands that are pre-established as to species composition (Johnstone et al., 2016). Such alterations substantially transform the soil microenvironment. Increases in temperature fluctuations and decreases in humidity also occur with windthrows due to the disruption of ecosystems. But these changes fundamentally affect ecosystem processes, the prevalence and distribution of life dwelling in soil habitats (Chapin et al., 2002).

Annelids are one of the most sensitive soil fauna to changes in environmental conditions and can be considered as bioindicators concerning these changes. Earthworms and enchytraeids plays an important role as ecosystem engineers in forest soils. They participate in several ecological processes by altering soil structure with burrows, regulating nutrient cycling via organic matter turnover and emissions of nutrients, and affecting microbial communities through their feeding activities (Blouin et al., 2013). However, we know very little about their responses to any post-gales forest regrowth. This review highlighted the effects of different forest regeneration practices, following windthrow events on soil annelids. These relationships are important for the sustainable management of soils under forest cover facing increasing climate change-induced extreme weather processes through which soil biodiversity and ecosystem functions can be affected.

Types of Regeneration and Their Implications

Natural Regeneration

Natural regeneration after windthrow disturbances includes processes like dispersal of seeds, and sprouting from residual roots or stumps. Most tree species can also sprout from leftover roots or stumps, speeding the recovery of forests (Vodde et al., 2010). Regeneration by this method is typically favored in forest ecosystems because it mimics a natural process. Natural windthrow sites, for instance, draw in some forest-dwelling organisms and contribute to ecological equilibrium (Żmihorski & Durska, 2010). It allows for the selection of species that are better adapted to local environmental conditions and thus fosters genetic diversity and increases resistance to pests and diseases. As a result, the mixed stands tend to create more stable, productive forests through time. One of the main drawbacks of natural regeneration is the comparatively slow rate at which forests recovers (Priewasser et al., 2013).

Artificial Regeneration

It utilizes methods mediated and non-mediated by humans like planting seedlings or direct seeding to accelerate and/or control forest recovery after disturbance such as windthrow. Planting seedlings includes planting seedlings raised in nurseries at the site of restoration, making it possible to choose specific species that are desirable for ecological or economic reasons (Kašák et al., 2017). The direct seeding method is

directly sowing seeds instead of using seedlings to re-establish forest cover and can be regarded as a more economical approach (Waldron et al., 2013). Tree cover is

established faster than if left to natural processes, reducing soil stabilization and short-term erosion (Priewasser et al., 2013). Human-assisted regeneration is often expensive as it entails high costs for planting, maintenance, and monitoring of large areas which can impose a limitation in widespread application (Duelli et al., 2019).

Table 1. Ecological factors affecting natural and artificial regeneration methods

Ecological Factor	Natural Regeneration	Artificial Regeneration	References
Soil Health	Improves over time through accumulation of organic matter and soil organism activity, such as annelids	Soil compaction and structural disruption, impacting biodiversity negatively	Duelli et al., 2019; Ilisson et al., 2007
Biodiversity	Supports a broader range of species by mimicking natural processes	Often results in monocultures or less diverse plant communities, reducing ecosystem resilience	Priewasser et al., 2013
Ecosystem Resilience	Enhances resilience due to greater biodiversity and natural soil health improvements	Initial rapid recovery, but potential long-term negative effects on biodiversity and ecosystem resilience	Thorn et al., 2017
Recovery	Slower establishment, requiring more time for ecosystems to reach a stable state	Faster initial recovery, beneficial for quick restoration needs	Vodde et al., 2010
Overall Ecological Impact	Promotes long-term biodiversity, soil health, and resilience, aligning with natural forest dynamics	Practical for immediate recovery but may compromise long-term ecological benefits	Duelli et al., 2019; Thorn et al., 2017

Effects of Windthrows on Forest Soil Properties

The impact of windthrow disturbance on important forest soil characteristics, such as moisture content, organic matter, and physical property has a direct and indirect consequences for soil ecosystems, and organisms that live in them (e.g. soil annelids). Soil moisture dynamics are altered on occasion due to windthrow events. Reduced tree canopy exposes the forest floor to more sunlight, thus increasing evaporation and changing moisture conditions (Mayer et al., 2017). Soil moisture can therefore be both directly and indirectly affected by windthrown trees: Immediately after windthrow, soil moisture may be overall higher because of high evaporative loss from transpiration but it may stabilize in the long term with new vegetation establishment (Seidl et al., 2017). Across the forest floor, windthrows mark an increase in organic matter due to fallen trees and branches decaying over time, which serves to enrich soil and enhance microbial activity. This influx helps to add on nutrient cycling and soil fertility. Heavily salvage logged areas have even been noted to have lower soil organic matter than unlogged sites as the removal of such organic material reduces its input to the soil, thus lead detrimental effect on nutrient availability and ecosystem function. Soil structure can be remarkably stressed by the physical disturbance of windthrow. Tree removal disturbs soil strata which may also lead to soil compaction, especially in areas where salvage logging is conducted with heavy machinery (Thomas et al., 2017). Soil compaction reduces their volume and promotes poor air and water infiltration limiting root growth and suppressing the natural habitat quality for soil organisms like annelids.

Importance of Soil Annelids in Ecosystem Processes

Soil annelids, due to their abundance and diversity in soil systems, primarily serve as a bio-indicator of soil ecosystem health. By decomposing organic matter and providing casts high in nutrients readily available for plant uptake (Amossé et al., 2016), as soil annelids are essential mediators of nutrient cycling. This not only fertilizes the soil but also facilitates plant growth, which in turn supports trophic levels above them. The same kind of burrowing activities also promote soil aeration and structure, allowing air and water to move in the annelid soil. These tunnels help in root respiration and microbial processes and ensure prevention of soil compaction which is critical for moisture retention and plant productivity (Amossé et al., 2016; Karhu et al., 2010). In addition, soil infauna, by providing passageways for decomposer microorganisms, has been shown to considerably expedite litter decomposition (e.g., Wang et al., 2010).

Natural Regeneration and Artificial Regeneration Implications on soil fauna

Annelids are affected by the long-term recovery of vegetation in naturally regenerating forests. Although low cover of organic matter may restrict annelid activity initially (Seidl et al., 2017), slow accumulation eventually favors annelids through their dispersal and resource competition abilities. Soil factors such as moisture and nutrients become favorable to annelids as vegetation begins to reinitiate (1986). Nonetheless, the slow accumulation of organic matter may limit their abundance at first (Mayer et al., 2014). But tree planting is a way of artificial regeneration — A method that works quickly in establishing vegetation, but it can also considerably disrupt pre-existing soil structures. Planting using mechanical disturbances can harm annelid habitats, which may cause losses in biodiversity (Duc et al., 2011). Fertilizer and soil amendment use during artificial regeneration can change soil chemistry that could be unfavorable for annelids. Although artificial methods can hasten the establishment of tree cover, they may not fulfill longer-term ecological functions as well as natural regeneration (Ilisson et al., 2007).

Comparative Implications of Regeneration Type

In contrast, natural regeneration is usually associated with higher annelid richness as organic matter builds up over time and vegetation becomes more diverse. Artificial regeneration, on the other hand, has been shown to decrease annelid diversity; soils under substantial mechanical disturbance or where disruption of nutrient dynamics occurred are possible explanations (Thorn et al., 2017). This research has been conducted in different regions which pinpoint these variations. Examples include temperate forests which often show higher annelid diversity and better soil quality after natural recovery from windthrow. Reductions in annelid numbers as a result of habitat disruption and modifications to soil properties caused by artificial regeneration have been reported for tropical regions (Mayer et al., 2014).

The positive and negative influences of windthrow disturbances on soil annelids

Strong winds significantly alter the soil environment, impacting soil annelids, which play a vital role in soil functionality. Windthrow events can create favorable conditions for annelids by increasing soil moisture and organic matter availability. Moist soils, which annelids favor, improve their mobility and feeding efficiency (Mayer et al., 2017). Fallen trees decompose, recycling nutrients into the soil and providing organic debris that supports annelid populations. This organic material enhances soil structure, facilitates nutrient cycling, and promotes soil aeration (Waldron et al., 2013; Royo et al., 2016). However, post-windthrow salvage logging can negatively affect soil health by compacting the soil with heavy machinery (Hanajík et al., 2017). Compacted soils limit annelid burrowing, restrict aeration, and reduce access to food sources (Fischer & Fischer, 2011). Additionally, intensive logging often removes essential organic debris, depriving annelids of critical resources (Šimonovičová et al., 2019). These disturbances disrupt nutrient cycling and slow the soil recovery process. While windthrow events can initially benefit annelids, improper management can negate these advantages and harm the soil ecosystem.

Knowledge Gaps

While there is a growing body of research on soil annelids and forest regeneration, several important knowledge gaps still exist:

Far-reaching Consequences: One of the major missing pieces of evidence is the impact of various regeneration strategies on soil annelids and their ecosystem services in a temporal context. Several studies focused on short-term outcomes, but the longer-term recovery trajectories of annelid communities and their effects on ecosystem engineers after disturbances have been little studied (Arias-Navarro et al., 2017).

Plausible Hypotheses Regional variability: Little is known about the regional climatic, soil, and biodiversity contexts that influence responses of soil annelids to natural versus artificial regeneration. This has rarely been replicated in situ, thus compromising the possibility to tailor management practices adapted to a particular site (Wubs et al., 2019), notably due to an underlying lack of understanding between these environmental determinants and regenerating strategies.

Mechanistic Understanding: A third knowledge gap lies in the mechanistic understanding of the role of soil annelids as either a driver or feedback to other soil biota-like microbial communities during forest regeneration. How these coupled processes of nutrient cycling and soil organic matter formation mediated by annelid activity vary among different forest recovery scenarios remains poorly defined (Rahbarisisakht et al., 2021).

Future Directions

Future research should put priority on addressing the following issues to fill up these knowledge gaps; Longitudinal studies are needed to monitor the recovery and functioning of soil annelid populations in diverse forest types. Such studies can help us to better understand the long-term effects of these regeneration strategies on annelid community dynamics, ultimately providing crucial information for sustainable forest management (Arias-Navarro et al., 2017). Regional comparative studies covering different regions and forest ecosystems would be useful to explain how environmental variables, for instance, climate or soil type, affect annelid responses to regeneration. Such an approach would yield a greater understanding of how adaptable and ecologically significant annelid communities are in varying ecological scenarios (Kosewska et al., 2018). Mechanistic studies highlighted the critical roles of soil annelids in microbial composition and functional profiles, a future direction could be to try to elucidate the mechanistic basis through which the organisms interact with microbial communities or cycle nutrients during forest regeneration. Filling in these gaps can improve our understanding of how forest regeneration strategies interact with soil biota, ultimately allowing us to better manage soils for health, biodiversity, and ecosystem resilience.

Conclusion

Soil annelids are a foundation species in forest ecosystems because they contribute strongly to nutrient cycling, soil structure, and organic matter decomposition. This also has significant implications for survival, population dynamics, and ecological function of annelids as regeneration strategy (natural versus artificial) plays an important role here. Natural regeneration generally promotes more annelids diversity and activity by the gradual accumulation of organic matter and complex plant community establishment. In contrast, the intention of artificial regeneration – which is often accompanied by soil disturbance – could lead to reduced or even absent annelid populations.

References

Amossé, J., Dózsa-Farkas, K., Boros, G., Rochat, G., Sandoz, G., Fournier, B., Le Bayon, R. C., 2016. Patterns of earthworm, enchytraeid and nematode diversity and community structure in urban soils of different ages. European Journal of Soil Biology, 73, 46-58.

Arias-Navarro, C., Díaz-Pinés, E., Klatt, S., Brandt, P., Rufino, M. C., Butterbach-Bahl, K., Verchot, L. V., 2017. Spatial variability of soil N2O and CO2 fluxes in different topographic positions in a tropical montane forest in Kenya. Journal of Geophysical Research: Biogeosciences, 122(3), 514-527.

Blouin, M., Hodson, M. E., Delgado, E. A., Baker, G., Brussaard, L., Butt, K. R., Brun, J. J., 2013. A review of earthworm impact on soil function and ecosystem services. European Journal of Soil Science, 64(2), 161-182.

Bouget, C., Duelli, P., 2004. The effects of windthrow on forest insect communities: a literature review. Biological conservation, 118(3), 281-299.

Chapin, F. S., Matson, P. A., Mooney, H. A., Vitousek, P. M., 2002. Principles of terrestrial ecosystem ecology.

Duelli, P., Wermelinger, B., Moretti, M., & Obrist, M. K. (2019). Fire and windthrow in forests: Winners and losers in Neuropterida and Mecoptera. Alpine Entomology, 3, 39-50.

Fischer, J., Lindenmayer, D. B., 2002. The conservation value of paddock trees for birds in a variegated landscape in southern New South Wales. 2. Paddock trees as stepping stones. Biodiversity & Conservation, 11, 833-849.

Hanajík, P., Gáfriková, J., & Zvarík, M., 2017. Dehydrogenase activity in topsoil at windthrow plots in Tatra National Park. Central European Forestry Journal, 63(2-3), 91-96.

Ilisson, T., Köster, K., Vodde, F., Jõgiste, K., 2007. Regeneration development 4–5 years after a storm in Norway spruce dominated forests, Estonia. Forest Ecology and Management, 250(1-2), 17-24.

Johnstone, J. F., Allen, C. D., Franklin, J. F., Frelich, L. E., Harvey, B. J., Higuera, P. E., Turner, M. G., 2016. Changing disturbance regimes, ecological memory, and forest resilience. Frontiers in Ecology and the Environment, 14(7), 369-378.

Karhu, K., Fritze, H., Tuomi, M., Vanhala, P., Spetz, P., Kitunen, V., Liski, J., 2010. Temperature sensitivity of organic matter decomposition in two boreal forest soil profiles. Soil Biology and Biochemistry, 42(1), 72-82.

Kašák, J., Foit, J., Hučín, M., 2017. Succession of ground beetle (Coleoptera: Carabidae) communities after windthrow disturbance in a montane Norway spruce forest in the Hrubý Jeseník Mts.(Czech Republic). Central European Forestry Journal, 63(4), 180-187.

Kosewska, A., Topa, E., Nietupski, M., Kędzior, R., 2018. Assemblages of carabid beetles (Col. Carabidae) and ground-dwelling spiders (Araneae) in natural and artificial regeneration of pine forests. Community Ecology, 19(2), 156-167.

Mayer, M., Sandén, H., Rewald, B., Godbold, D. L., Katzensteiner, K., 2017. Increase in heterotrophic soil respiration by temperature drives decline in soil organic carbon stocks after forest windthrow in a mountainous ecosystem. Functional Ecology, 31(5), 1163-1172.

Priewasser, K., Brang, P., Bachofen, H., Bugmann, H., Wohlgemuth, T., 2013. Impacts of salvage-logging on the status of deadwood after windthrow in Swiss forests. European Journal of Forest Research, 132, 231-240.

Rahbarisisakht, S., Moayeri, M. H., Hayati, E., Sadeghi, S. M. M., Kepfer-Rojas, S., Pahlavani, M. H., Borz, S. A., 2021. Changes in soil's chemical and biochemical properties induced by road geometry in the Hyrcanian temperate forests. Forests, 12(12), 1805.

Royo, A. A., Peterson, C. J., Stanovick, J. S., Carson, W. P., 2016. Evaluating the ecological impacts of salvage logging: can natural and anthropogenic disturbances promote coexistence?. Ecology, 97(6), 1566-1582.

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Reyer, C. P., 2017. Forest disturbances under climate change. Nature climate change, 7(6), 395-402.

Shorohova, E., Aakala, T., Gauthier, S., Kneeshaw, D., Koivula, M., Ruel, J. C., Ulanova, N., 2023. Natural disturbances from the perspective of forest ecosystem-based management. In Boreal Forests in the Face of Climate Change: Sustainable Management (pp. 89-121). Cham: Springer International Publishing.

Šimonovičová, A., Kraková, L., Piecková, E., Planý, M., Globanová, M., Pauditšová, E., Pangallo, D., 2019. Soil microbiota of dystric cambisol in the High Tatra Mountains (Slovakia) after windthrow. Sustainability, 11(23), 6851.

Thorn, S., Bässler, C., Brandl, R., Burton, P. J., Cahall, R., Campbell, J. L., Müller, J., 2018. Impacts of salvage logging on biodiversity: A meta-analysis. Journal of Applied Ecology, 55(1), 279-289.

Vodde, F., Jõgiste, K., Gruson, L., Ilisson, T., Köster, K., Stanturf, J. A., 2010. Regeneration in windthrow areas in hemiboreal forests: the influence of microsite on the height growths of different tree species. Journal of Forest Research, 15(1), 55-64.

Waldron, A., Mooers, A. O., Miller, D. C., Nibbelink, N., Redding, D., Kuhn, T. S., Gittleman, J. L., 2013. Targeting global conservation funding to limit immediate biodiversity declines. Proceedings of the National Academy of Sciences, 110(29), 12144-12148.

Waldron, K., Ruel, J. C., Gauthier, S., De Grandpré, L., Peterson, C. J., 2014. Effects of post-windthrow salvage logging on microsites, plant composition and regeneration. Applied vegetation science, 17(2), 323-337.

Wohlgemuth, T., Schwitter, R., Bebi, P., Sutter, F., Brang, P., 2017. Post-windthrow management in protection forests of the Swiss Alps. European Journal of Forest Research, 136, 1029-1040.

Wubs, E. J., van Der Putten, W. H., Mortimer, S. R., Korthals, G. W., Duyts, H., Wagenaar, R., Bezemer, T. M., 2019. Single introductions of soil biota and plants generate long-term legacies in soil and plant community assembly. Ecology Letters, 22(7), 1145-1151.

Żmihorski, M., & Durska, E., 2011. The effect of contrasting management types on two distinct taxonomic groups in a large-scaled windthrow. European Journal of Forest Research, 130, 589-600.

Revisiting the sustainable development prospects of qanat systems in resettlement efforts in The Liberated Eastern Zangezur

Alovsat GULIYEV [1,*], Rahila ISLAMZADE [1], Tunzala BABAYEVA [2], Tarlan YELMARLI [1]
[1] Institute of Soil Science and Agrochemistry, Baku, Azerbaijan
[2] Sumgayit State University, Sumgayıt, Azerbaijan

***Corresponding Author**

Alovsat GULIYEV
elovset_q@mail.ru

Abstract

The Jabrayil district of Eastern Zangezur is situated in a region that is almost devoid of river systems. For millennia, the local population has relied on qanats (traditional underground water channels) and, in some areas, springs to meet their drinking and irrigation water needs. This study investigates the water quality associated with qanat systems in the Jabrayil district of Azerbaijan's Eastern Zangezur region. Water samples were collected from several qanats: Kichik Kehriz in Dash Veysalli village, Aghalarbay Kehriz in Kavdar village, Taveka Kehriz in Chereken village, Shıxı Kehriz in Horovlu village, Xalifa Deresi Kehriz, Asger Kehriz, Orta Kehriz, and Quzey Kehriz in Quycaq village. Various physicochemical properties of these samples were analyzed. The quality parameters examined included pH, electrical conductivity (EC), hardness, mineralization, and concentrations of ions such as calcium, magnesium, and sodium. Additional parameters like TDS (total dissolved solids), SAL (salinity), DO (dissolved oxygen measured in mg/l and percentage), and radiation levels were also assessed. The results indicated that the qanat water is generally of high quality, with pH levels suitable for both drinking and irrigation purposes. However, some qanat systems exhibited high electrical conductivity and mineralization, pointing to potential salinity issues for salt-sensitive crops. In terms of free ions, calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations varied significantly. Calcium ranged from 5610 mg/l to 10820 mg/l, while magnesium levels were between 1090 mg/l and 2430 mg/l. The analysis revealed that all samples exceeded these limits, indicating potential risks for direct consumption. However, with proper management, the water remains suitable for irrigation. This study highlights the importance of qanat systems in arid and semi-arid regions and provides practical recommendations for improving the socio-economic well-being of local populations, as well as sustainable land and water resource management.

Keywords: Qanat system, Agricultural impact, Eastern Zangezur region, Water management

Introduction

The qanat is a hydraulic structure created through human ingenuity that brings groundwater to the surface using natural flow. It provides consistent, pure, and clean water year-round, independent of seasonal variations, while also serving as a natural drainage system and positively influencing the environment. Globally, Azerbaijan ranks fourth in the use of qanat water. The study of qanats offers valuable insights into Azerbaijan's historical past, lifestyle, ethnogenesis, and ethnography. Qanats in the foothill regions, endowed with great potential, are also considered cultural heritage monuments (Guliyev, 2016; 2021; Guliyev et al., 2024; Pasha et al., 2023).

Today, the restoration and scientific development of qanats are crucial as they could emerge as a reliable water system during periods of water scarcity. Particularly in the era of climate change, qanats play a significant role in efficiently utilizing groundwater resources and maintaining their stability. The modern scientific management and incorporation of advanced technologies into the operation of these ancient water systems will facilitate easier and more reliable exploitation of groundwater in the future (Nasiri and Mafakheri, 2015; Mansouri Daneshvar et al., 2023).

In the modern era, the challenges of securing potable and irrigation water are exacerbated by climate change (e.g., reduced or disrupted precipitation, extreme heat events) and ecological imbalances (e.g., soil erosion, degradation, and altered water retention and infiltration capacities). These issues are becoming increasingly critical (Babayeva et al., 2024).

The primary aim of this study is to investigate, for the first time, the ancient qanat systems in the liberated territories of Eastern Zangezur and to assess their role in the resettlement of these areas. The research focuses on identifying the reasons for the dysfunction of these systems, pinpointing damaged sections, and determining the feasibility of their restoration.

In water-scarce regions like Azerbaijan, qanat systems have historically been vital in meeting the demand for both irrigation and drinking water. By understanding and rehabilitating these systems, the study seeks to provide sustainable solutions for water supply in the region.

Material and Methods

The Jabrayil district of Eastern Zangezur is characterized by its unique hydrogeological conditions. In the alluvial and deluvial zones of the region, groundwater lies at relatively deeper levels, leading to lower mineralization. In contrast, in the plain areas where groundwater is closer to the surface, the degree of mineralization is higher. These hydrogeological factors have resulted in the formation of hydromorphic soils and facilitated salinization and carbonization of the land. Depending on the chemical composition of groundwater, salinization primarily manifests as sulfate and soda types.

Located in the southeastern part of the Lesser Caucasus Mountains, on the left bank of the Araz River, the liberated Jabrayil district is situated in the southern region of Azerbaijan. It borders the Islamic Republic of Iran to the south, Zangilan to the southwest, Gubadli to the west, Khojavend to the north, and Fuzuli to the east. Covering an area of 1,049 square kilometers, the district is predominantly mountainous and lacks a river network. Historically, the local population relied on kahriz systems and springs to meet their drinking and irrigation water needs.

During the 20th century, Jabrayil had 111 qanat systems, providing an average of 34 million cubic meters of water annually for drinking and irrigation. The district was occupied by Armenian forces in 1993 and liberated in 2020. Since the area was heavily mined during the occupation, demining operations have been ongoing, enabling research into qanat systems in certain parts of the region. Restoring the destroyed qanats holds significant potential for alleviating the country’s water scarcity challenges.

The Jabrayil qanats are primarily fed by groundwater formed from rain and snowmelt accumulating in mountain river valleys. While springs are also present in some areas, qanat systems have been the primary water source for the local population for centuries. Although qanat water flow decreases during dry periods, it does not completely cease, making them a reliable water source year-round.

In recent years, global attention from scientists and policymakers has highlighted the importance of qanat systems. These ancient hydraulic structures have proven to be eco-friendly, causing no harm to ecosystems, and are considered the most reliable water sources in arid zones. Studying qanats not only facilitates a better understanding of the region but also enables planning for future water challenges on a national scale.

Results and Discussion

Following the initiation of monitoring activities on qanats in the liberated and demined territories, water samples were collected from the study area's qanats for physicochemical analysis. These analyses were conducted at the Institute of Geology and Geophysics of the Azerbaijan National Academy of Sciences.

Water samples were taken from several qanats in Jabrayil, including Kichik Kehriz (Dash Veysalli village), Aghalarbey Kehriz (Kavdar village), Taveka Kehriz (Chereken village), Shıxı Kehriz (Horovlu village), Xalifa Deresi Kehriz, Asger Kehriz, Orta Kehriz, and Quzey Kehriz (Quycaq village). The results indicated that the water from these qanats is fully suitable for both drinking and irrigation purposes.

The turbidity of the qanats water ranged from 0.21 to 2.5 mg/l, staying below the permissible limit of 2.6 mg/l. The only exception was the sample from Kichik Kehriz in Dash Veysalli village, which showed slightly higher turbidity at 2.71 mg/l. This anomaly was attributed to urban development and reconstruction activities in the area carried out by some Turkish companies. Specifically, the shallow depth of the kehriz wells (below 4-5 meters) made the tunnels susceptible to collapse under the influence of heavy machinery operating above.

Table 1. Analysis results of samples taken from the qanat waters of the Jabrayil region

N/N	Point description	pH	EC msm/cm	TDS mg/L	SAL %	DO %	DO mg/L	T oC	Rad µSv/h
1	Horovlu village Asger kehriz	8,06	644	322	0,03	98,4	8,33	21,1	0,001
2	Horovlu village Orta kehriz	7,88	302	371	0,04	95,6	8,48	21,2	0,001
3	Village center Chinar kehriz	7,80	407	203	0,02	97,9	8,46	21,1	0,001

Note: The analyses were carried out in the relevant laboratory of the Radiation Problems Institute of the Ministry of Emergency Situations of the Republic of Azerbaijan.

Overall, the findings confirm that the water from these qanats is suitable for use in drinking water supply, highlighting their continued importance in addressing water needs in the liberated territories.

Thus, the analysis of the spring water taken from the combat zone was carried out in the relevant laboratory of the Radiation Problems Institute. The results of the analysis are presented in a table and explanatory form.

It should be noted that in the table, EC refers to Electrical Conductivity, TDS to Total Dissolved Solids, SAL to Salinity, DO to Dissolved Oxygen (in percentage and mg/l), and Rad represents radiation.

As seen in Table 1, based on the analysis results, no foreign substances, particularly heavy metals, were found. This indicates that the indicators in the examined area are within permissible limits.

The qanat water was analyzed for the purpose of studying its impact on soil fertility improvement and productivity when used for irrigation in the foothill zones. The full chemical analysis of the qanat waters used for drinking and irrigation in the villages of Amirvarli, Fuqanli, Qaracalli, and others in the Jabrayil region was conducted. The analysis results are presented in Table 2.

For comparison, analyses were conducted between the Chinar kehriz, located at 807 meters above sea level in the Binederesi area, and the Amirvarli village kehriz at 154 meters above sea level. In addition, springs at intermediate elevations in the villages of Fuqanli (384 m), Niyazqulular (328 m), and Qaracalli (613 m) were also analyzed. Such variation is in line with natural law.

As shown in Table 2, the hardness of the qanat water is normal, with pH ranging from 7.8 to 8.02. The permissible limit for sodium is 200 mg/l, but the sodium content ranged from 1.77 to 98.42 mg/l (the amount of Na increases as you approach the Araz River). The potassium (K) content, with a permissible limit of 50 mg/l, was 2.16 mg/l in Amirvarli, 0.36 mg/l in Binederesi, and 55.45 mg/l only in Fuqanli. The permissible limit for calcium (Ca) is 180 mg/l, with the values being 120.24 mg/l in Amirvarli and 66.40 mg/l in Binederesi. The magnesium (Mg) content is 40 mg/l, but it was 33.11 mg/l in Amirvarli and 6.70 mg/l in Binederesi. The concentrations of aluminum (Al) and iron (Fe) are very low and much below the permissible limits.

The permissible limit for sulfates is 500 mg/l, whereas the values are 42.84 mg/l in Amirvarli village and 2.15 mg/l in Binederesi. Carbonates in the area range from 495.5 to 120.90 mg/l.

For chlorides, the permissible limit is below 350 mg/l. The values are 61.74 mg/l in Amirvarli village and 1.34 mg/l in Binederesi village. The silicon content is up to 10 mg/l, with Amirvarli showing 16.17 mg/l and Binederesi 2.52 mg/l. The variation in silicon levels is also considered natural.

In general, the concentrations of bromine, strontium, cadmium, mercury, lead, zinc, chromium, copper, selenium, manganese, and arsenic in the spring waters are significantly below permissible limits. The dry residue content in the water samples taken from the area, with a normative range of 1000–1500 mg/l, fluctuates between 701.89 mg/l and 203.3 mg/l in the analyses. This indicates that the mineralization of the waters, based on dry residue, is considerably lower than the normative values.

Conclusion

This study provides a detailed assessment of the water quality and soil characteristics associated with qanat systems in the Cebrail district of the Eastern Zangezur region, Azerbaijan. The analysis of water samples from seven qanat systems revealed generally high-quality water with minimal contamination, suitable for both drinking and irrigation purposes. However, certain qanat systems exhibited higher mineral content and salinity, indicating the need for careful management to prevent soil salinization and ensure sustainable use.

By integrating traditional qanat systems with modern agricultural practices, the sustainability and productivity of these systems can be enhanced, contributing to the socio-economic well-being of local communities in the Eastern Zangezur region.

Table 2. Complete Chemical Analysis of Qanat Waters

Water content	Amirvarli	Binederesi	Fuğanlı	Niyazqulular (spring)	Qaracallı (monument)	Standart
The hardness	8,77	3,87	14,54	8,28	5,30	---
pH	7,80	8,02	7,99	8,01	8,15	---
Na	98,42	1,7711	16,92	49,38	2,19	200
K	2,16	0,36	55,45	30,44	15,93	50
Ca	120,24	66,40	275,22	141,49	96,64	180
Mg	33,11	6,70	9,45	14,52	5,73	40
Al	0,029	0,031	0,039	0,048	0,042	0,5
Fe	0,15	0,14	0,11	0,13	0,12	<03
Sulfat	42,84	2,15	21,06	12,96	2,19	<<500
Carbonate	326,14	120,90	495,50	323,24	170,34	---
Cl	61,74	1,34	9,54	19,32	3,14	<350
Si	16,17	2,52	17,37	8,52	4,38	10
Br	0,02	0,03	0,04	0,05	0,07	0,2
Sr	0,84	0,91	1,12	0,95	0,87	7
Cd	0,0004	0,0005	0,0003	0,0003	0,0004	0,001
Hg	0,0001	0,0002	0,0001	0,0002	0,0001	0,0005
Pb	0,002	0,001	0,003	0,001	0,003	0,03
Zn	0,005	0,009	0,008	0,007	0,004	1
Cr	0,009	0,008	0,012	0,011	0,008	0,1
Cu	0,009	0,016	0,017	0,024	0,028	1
Se	0,0005	0,0002	0,0003	0,0003	0,0005	0,01
Mn	0,012	0,014	0,021	0,012	0,011	0,1
As	0,002	0,003	0,004	0,002	0,005	0,05
Dry residue	701,89	203,30	901,88	601,10	301,70	1000(1500)
Coordinat Latitude	39.296451	39.452005	39.351899	39.257520	39.470299	-
Coordinat Longtitude	47.076540	47.005217	47.088041	46.955593	47.088776	-
Altitude (m)	154	807	384	328	613	-

Note: The analyses were carried out in the relevant laboratory of the Geology and Geophysics Institute of the Ministry of Science and Education of the Republic of Azerbaijan.

Acknowledgments

This work was supported by the Azerbaijan Science Foundation (Grant No: AEF-MQM-QA-2-2023-3(45)-05/05/3-M-05).

References

Babayeva, T., Guliyev, A., İslamzade, T., İslamzade, R., Haciyeva, X., Ashurova, N., Aliyeva, A., Maksudov, S., 2024. Impacts of irrigation with Cd-contaminated water from Sugovushan Reservoir, Azerbaijan on total cadmium and its fractions in soils with varied textures. Eurasian Journal of Soil Science 13(2): 145-152.

Guliyev, A., 2016. Evolution of the qanat (kahriz) systems in the arid countries of the caucasus and central Asia. In: Underground aqueducts handbook. Angelakis, A.N., Chiotis, E.D., Eslamian, S., Weingartner, H. (Eds.). CRC Press. pp.323-332.

Guliyev. A., 2021. Azerbaijan Ganats.Elm, Azerbaijan 256 p. Available at [Access date: 04.02.2024]: https://www.tai.az/static/img/pdf/120436d0-e312-4270-ab93-5ac2c181c285.pdf

Guliyev A, Babayeva T., Islamzade R., Islamzade T., Yelmarlı T., Nesirov E., Aliyeva A., Ashurova N., 2024. Sustainable agriculture through qanat systems in Karabakh: Water and soil characteristics in the context of climate change. Eurasian Journal of Soil Science 13(4): 303-311.

Mansouri Daneshvar, M.R., Ebrahimi, M., Ahmadi, F.S., 2023. Efficiency assessment of the environmental variables in the Qanat systems based on major hydrological basins in Iran. Applied Water Science 13: 99.

Nasiri, F., Mafakheri, M.S., 2015. Qanat water supply systems: a revisit of sustainability perspectives. Environmental Systems Research 4: 13.

Pasha, N.H., Zengin, E., Bayarli, A.T., 2023. Sustainability of water resources of Azerbaijan, future prospects and problems. Journal of Management, Economics, and Industrial Organization 7(2): 24-37.

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

Ecological impact of imazamox: Effects on soil microbial activity and functional diversity

Anupriya ASOK KUMAR SREEKALA *, Katya DIMITROVA
Agricultural University – Plovdiv, Faculty of Plant Protection and Agroecology, Department of Microbiology and Environmental Biotechnologies, Plovdiv, Bulgaria

***Corresponding Author**

Anupriya ASOK KUMAR SREEKALA
anuasok20@gmail.com

Abstract

This review explores the multifaceted effects of the herbicide imazamox on soil microbial activity, functional diversity, in relation to the overall soil health, synthesizing findings across various studies to highlight both immediate and long-term impacts. Research indicates that imazamox application initially alters microbial diversity, often by decreasing sensitive bacterial species while promoting certain fungi and actinomycetes. Studies show that imazamox affects microbial community composition based on soil type, with greater availability in sandy soils and reduced impact in soils rich in organic carbon. The herbicide also influences key microbial functions, such as enzyme activity and nitrogen cycling. Enzyme activities, particularly dehydrogenase and nitrogen-cycling enzymes, frequently decrease shortly after imazamox application, but microbial communities generally build up a resilience over time. While short-term studies consistently report declines in microbial diversity and enzyme activity, long-term observations reveal adaptive responses and the emergence of imazamox-tolerant species. Differences in study outcomes are often attributed to geographic and methodological variability, with greenhouse studies showing more pronounced effects than field studies. Overall, imazamox's ecological impact appears to diminish over time, as microbial communities adapt, stabilize, and sometimes increase in diversity, potentially forming a unique equilibrium shaped by selective pressures from the herbicide. This synthesis provides a nuanced understanding of imazamox's effects on soil ecosystems, with implications for sustainable herbicide management and agricultural practices.

Keywords: Enzyme Activity, Imazamox, Soil, Soil Microbial Diversity, Sustainable Agriculture

Introduction

As global food demands rise alongside population growth, optimizing crop production has become essential, leading to a marked increase in agro-chemical use in intensive farming practices. Among these chemicals, herbicides play a critical role in controlling weeds, which are a major threat to modern farming due to their negative impact on crop yield and quality (Abouziena & Haggag, 2016). Imazamox, a post-emergence imidazolinone herbicide, is widely used to manage broadleaf weeds and certain grasses by inhibiting the acetolactate synthase (ALS) enzyme (Epa & of Pesticide Programs, 1997), effectively disrupting protein and DNA synthesis and leading to plant death (Tan et al., 2005; Vasic et al., 2022). Notably, the relatively fast degradation rate of imazamox compared to other imidazolinones (Bundt et al., 2015) has made its application a valuable tool in weed management strategies (Kizildağ et al., 2014). However, the increased application of herbicides like imazamox has raised concerns about their unintended effects on non-target soil microorganisms (Parven et al., 2024), which play essential roles in nutrient cycling, organic matter decomposition, and overall soil health (García-Delgado et al., 2019; Parven et al., 2024).

Microbial communities in the soil are not only crucial for maintaining soil fertility but also serve as indicators of soil health and ecosystem stability (Sharma et al., 2010). When pesticides accumulate in soils beyond threshold levels, they can disrupt abundance, diversity, and function of microbial communities. Herbicides may exert both direct and indirect toxic effects on soil microbiota, including changes in microbial composition (Vasic et al., 2022; Walder et al., 2022) enzyme production, and the physiological processes necessary for nutrient cycling (Duke, 2018; Jeyaseelan et al., 2024).Additionally, the persistence of herbicides like imazamox is influenced by factors such as temperature, moisture, soil clay content, and organic matter (Shaner, 2014), all of which determine how these chemicals interact within soil ecosystems over time (Sagliker & Ozdal, 2021; Ulbrich et al., 2005). With half-life estimates for imazamox ranging from 35 to 118 days (Sagliker & Ozdal, 2021) depending on soil type and environmental conditions, understanding its impact on soil microbiota becomes increasingly relevant for sustainable agricultural practices (Pannacci et al., 2007; Shaner, 2014).

This review examines the existing research on the effects of imazamox on soil microbial communities, focusing on its influence on key microbial groups such as bacteria, fungi, and actinomycetes. It incorporates findings from both field and laboratory studies to evaluate the short- and long-term impacts of imazamox on microbial diversity, activity, and overall soil functionality.

While significant progress has been made in understanding the immediate effects of imazamox on microbial populations, important gaps remain. Specifically, there is a need for standardized methodologies and more comprehensive long-term studies to better elucidate the herbicide's broader ecological implications (Jeyaseelan et al., 2024; Vasic et al., 2022).

By critically analyzing current methodologies and findings, this review provides a detailed overview of imazamox's effects on soil microorganisms and identifies key areas for future research, offering valuable insights for advancing sustainable agricultural practices.

Imazamox's Impact on Microbial Diversity

The effects of imazamox on soil microbial diversity are complex and often vary depending on soil characteristics, organic content, and ecological conditions. Studies consistently demonstrate that imazamox affects microbial diversity, sometimes increasing certain species while reducing others. For example, Pannacci et al. (2006) found that imazamox availability was highest in sandy soils and lower in soils rich in organic carbon, influencing microbial communities differently based on soil type. Kizildag (2014) further confirmed that imazamox impacts cumulative carbon mineralization rates, with notable differences between soil types. In the study by Farman Ali (2024) was shown that applying an imidazoline-based herbicide (IM) to wheat rhizospheres increased microbial richness and diversity. IM reduced the relative abundance of Ralstonia pickettii and an unidentified Ancylothrix species, likely due to IM-degrading microbes or saprophytic growth on sensitive organisms' biomass. These findings suggest that the herbicide may encourage the growth of specific microbial species capable of utilizing imazamox as a carbon source. The results from study implied that The IM herbicide had a stimulatory influence on the dynamics of microbial communities, in particular bacterial communities (Ali et al., 2024).

Similarly, Pinna (2022) demonstrated that imazamox modifies soil microbial communities by enhancing the proliferation of specific groups, such as actinomycetes within the Streptomycetaceae family and Pseudomonas spp., and exhibits considerable potential for microbial degradation. This finding is further corroborated by work of Ling Ge (2022), who isolated two Streptomycetaceae strains, JX02 and JX06, both of which were shown to effectively degrade imazamox (Ge et al., 2022; Pinna et al., 2022).

Other studies, Lupwayi et al. (2003), reported decrease of microbial diversity when imazamox was combined with other herbicides in a controlled greenhouse setting, although the same effect was not consistently observed in the field experiments. The inconsistency in the findings illustrate that while imazamox can boost microbial diversity in some cases, it may also suppress specific microbial taxa, depending on local environmental factors (Lupwayi et al., 2004).

Functional Changes in Microbial Communities

Imazamox significantly influences microbial enzyme activities and nutrient cycling functions, particularly during the initial stages after application. Soil enzyme activity, which is a key indicator of microbial function, often shows a temporary decline following imazamox treatment. For example, dehydrogenase activity, an indicator of overall microbial activity, typically decreases shortly after imazamox application, as shown in studies by Kaur (2022) and Vasic (2022). However, microbial resilience is often observed, with enzyme activities rebounding over time, indicating adaptation by soil microbes. (Kaur et al., 2020; Vasic et al., 2022).

Additionally, imazamox affects nitrogen cycling, an essential component of soil nutrient dynamics. Sim et al. (2022) noted that imazamox inhibited specific nitrogen-cycling enzymes, such as N-acetylglucosaminidase, particularly in nutrient-rich soils where nitrifying bacteria play a crucial role. Sagliker (2021) observed that imazamox reduced nitrate-producing bacterial activity, which lowered nitrogen mineralization rates. Over time, however, some soil microbes began to adapt, indicating that while imazamox may disrupt microbial functions initially, microbial communities often develop the ability to metabolize the herbicide as an energy source (Kizildağ et al., 2014; Sagliker & Ozdal, 2021; Sim et al., 2022).

Short-Term vs. Long-Term Effects

The short-term effects of imazamox on microbial communities are usually characterized by an initial reduction in microbial populations and shifts in microbial community composition. Studies showed that within weeks of application, imazamox lowers microbial biomass and diversity, as seen in Lupwayi et al. (2003), who observed reduction in microbial carbon and altered community structure immediately after treatment. These short-term changes are often attributed to the herbicide's immediate toxicity to sensitive microbial taxa.

In contrast, long-term studies suggest that microbial communities may exhibit resilience and adapt to exposure of imazamox over time. For instance, Smith et al. (2018) documented a rebound in microbial diversity, with communities gradually shifting toward herbicide-tolerant species that flourish under selective pressure. Similarly, Vasic (2019) noted a resurgence of actinomycetes and fungi populations in forest soils treated with imazamox, suggesting that repeated application might foster a stable community of resilient species. This rebound effect highlights the adaptability of microbial communities to herbicide exposure, particularly when imazamox is applied at recommended doses.

Across studies, imazamox's impact on soil microbial communities is shaped by a range of variables, including geographic location, soil type, and research methodology. For instance, studies conducted in Mediterranean climates, such as Kizildag (2014), reported higher carbon mineralization rates, whereas studies in some temperate regions of Canada (Lupwayi et al. 2003) revealed greater microbial sensitivity to imazamox, likely due to soil composition differences. Methodological differences also play a role; greenhouse studies often exhibit more pronounced herbicide effects due to controlled conditions, while field studies sometimes show milder or less consistent impact.

These comparisons underscore the importance of standardized methodologies to assess imazamox's ecological effects accurately. While short-term research highlights a decline in microbial diversity and enzyme activity, long-term studies reveal microbial communities' adaptive capacity. In general, although imazamox can disrupt soil microbiota initially, microbial ecosystems tend to stabilize over time, leading to potential shifts in microbial composition and functionality.

Conclusion

This review underscores the nuanced and dynamic relationship between imazamox and soil microbial communities, revealing both challenges and opportunities for sustainable agricultural management. While imazamox initially disrupts microbial diversity, enzymatic activities, and nutrient cycling, its effects are not uniformly detrimental. Microbial communities often demonstrate remarkable resilience, with long-term studies showing recovery and adaptation. This adaptive response showcases the capacity of soil ecosystems to mitigate anthropogenic stressors. However, such resilience is contingent upon factors like soil type, organic content, and environmental conditions. An important insight is the role of imazamox as driving force towards shifts in microbial community that favor species capable of degrading the herbicide, potentially creating a feedback mechanism that reduces its persistence over time. This offers a dual benefit: mitigating long-term soil toxicity while fostering microbial populations that can enhance soil health. However, the promotion of selective microbial groups could inadvertently suppress other beneficial taxa, raising questions about the balance between resilience and biodiversity.

The stark differences between greenhouse and field studies highlight the importance of conducting research in real-world conditions. Controlled experiments are invaluable for understanding mechanisms but may overestimate the herbicide's impact compared to more variable field environments. This divergence calls for harmonized methodologies to bridge the gap between experimental and applied research.

Overall, while imazamox's ecological footprint appears manageable over time, its short-term disruptions to soil function necessitate careful consideration of application timing, dosage, and complementary soil management practices. Integrating crop rotation, organic amendments, and microbial inoculants could further enhance soil resilience and ensure the herbicide's role in sustainable farming systems. These insights point to the need for a holistic approach to herbicide use, balancing immediate agricultural needs with long-term soil health and ecosystem stability

References

Abouziena, H. F., & Haggag, W. M., 2016. Métodos alternativos de controle não químicos de plantas daninhas: Uma revisão. Planta Daninha, 34(2), 377–392. https://doi.org/10.1590/S0100-83582016340200019

Ali, F., Zhaocheng, T., Gangao, M., Zhang, B., Xitie, L., Zeyu, Q., 2024. Taxonomic and functional changes in wheat rhizosphere microbiome caused by imidazoline-based herbicide and genetic modification. Environmental Research, 119726. https://doi.org/10.1016/j.envres.2024.119726

Bundt, A. C., Avila, L. A., Pivetta, A., Agostinetto, D., Dick, D. P., Burauel, P., 2015. Imidazolinone Degradation in Soil in Response to Application History. Planta Daninha, 33(2), 341–349. https://doi.org/10.1590/0100-83582015000200020

Duke, S. O., 2018. Interaction of Chemical Pesticides and Their Formulation Ingredients with Microbes Associated with Plants and Plant Pests. Journal of Agricultural and Food Chemistry, 66(29), 7553–7561. https://doi.org/10.1021/acs.jafc.8b02316

Epa, U., & of Pesticide Programs, O., 1997. US EPA - Pesticides - Fact Sheet for Imazamox.

García-Delgado, C., Barba-Vicente, V., Marín-Benito, J. M., Mariano Igual, J., Sánchez-Martín, M. J., & Sonia Rodríguez-Cruz, M., 2019. Influence of different agricultural management practices on soil microbial community over dissipation time of two herbicides. Science of The Total Environment, 646, 1478–1488. https://doi.org/10.1016/j.scitotenv.2018.07.395

Ge, L., Wang, X., Hou, J.-W., Ni, Z.-J., Liu, W.-R., Bao, J., Wei, Y. L., 2022. Study on degradation characteristics of imazamox by Streptomycetaceae. Journal of Environmental Science and Health, Part B, 57(6), 470–478. https://doi.org/10.1080/03601234.2022.2064673

Jeyaseelan, A., Murugesan, K., Thayanithi, S., Palanisamy, S. B., 2024. A review of the impact of herbicides and insecticides on the microbial communities. In Environmental Research (Vol. 245). Academic Press Inc. https://doi.org/10.1016/j.envres.2023.118020

Kaur, P., Kaur, P., Kaur, N., Jain, D., Singh, K., Bhullar, M. S., 2020. Dissipation and phytotoxicity of imazethapyr and imazamox in soils amended with β-cyclodextrin-chitosan biocomposite. Science of The Total Environment, 735, 139566. https://doi.org/10.1016/j.scitotenv.2020.139566

Kizildağ, N., Sağliker, H., Cenkseven, Ş., Darici, H. C., Koçak, B., 2014. Effects of imazamox on soil carbon and nitrogen mineralization under Mediterranean climate. Turkish Journal of Agriculture and Forestry, 38(3), 334–339. https://doi.org/10.3906/tar-1303-52

Lupwayi, N. Z., Harker, K. N., Clayton, G. W., Turkington, T. K., Rice, W. A., Donovan, J. T., 2004. Soil microbial biomass and diversity after herbicide application.

Pannacci, E., Graziani, F., Covarelli, G., 2007. Use of herbicide mixtures for pre and post-emergence weed control in sunflower (Helianthus annuus). Crop Protection, 26(8), 1150–1157. https://doi.org/10.1016/j.cropro.2006.10.008

Parven, A., Meftaul, I. M., Venkateswarlu, K., Megharaj, M., 2024. Herbicides in modern sustainable agriculture: environmental fate, ecological implications, and human health concerns. In International Journal of Environmental Science and Technology. Springer Nature. https://doi.org/10.1007/s13762-024-05818-y

Pinna, M. V., Castaldi, P., Garau, M., Bianco, A., Multineddu, C., Cesarani, A., Sitzia, M., Diquattro, S., Mangia, N. P., Garau, G., 2022. Sorption–Desorption of Imazamox and 2,4-DB in Acidic Mediterranean Agricultural Soils and Herbicide Impact on Culturable Bacterial Populations and Functional Diversity. Agriculture (Switzerland), 12(11). https://doi.org/10.3390/agriculture12111862

Sagliker, H. A., Ozdal, N. K., 2021. How Do Imazamox Additions Affect Carbon and Nitrogen Mineralization in Sunflower Soil? Water, Air, and Soil Pollution, 232(12). https://doi.org/10.1007/s11270-021-05474-9

Shaner, D. L., 2014. Herbicide handbook. Weed Science Society of America.

Sharma, S. K., Ramesh, A., Sharma, M. P., Joshi, O. P., Govaerts, B., Steenwerth, K. L., Karlen, D. L., 2010. Microbial Community Structure and Diversity as Indicators for Evaluating Soil Quality (pp. 317–358). https://doi.org/10.1007/978-90-481-9513-8_11

Sim, J. X. F., Doolette, C. L., Vasileiadis, S., Drigo, B., Wyrsch, E. R., Djordjevic, S. P., Donner, E., Karpouzas, D. G., Lombi, E. 2022. Pesticide effects on nitrogen cycle related microbial functions and community composition. Science of the Total Environment, 807. https://doi.org/10.1016/j.scitotenv.2021.150734

Tan, S., Evans, R. R., Dahmer, M. L., Singh, B. K., Shaner, D. L., 2005. Imidazolinone-tolerant crops: history, current status and future. Pest Management Science, 61(3), 246–257. https://doi.org/10.1002/ps.993

Ulbrich, A. V., Souza, J. R. P., Shaner, D., 2005. Persistence and Carryover Effect of Imazapic and Imazapyr in Brazilian Cropping Systems 1 . Weed Technology, 19(4), 986–991. https://doi.org/10.1614/wt-04-208r2.1

Vasic, V., Hajnal-Jafari, T., Djuric, S., Kovacevic, B., Stojnic, S., Vasic, S., Galovic, V., Orlovic, S., 2022. Effect of Herbicide Clopyralid and Imazamox on Dehydrogenase Enzyme in Soil of Regenerated Pedunculate Oak Forests. Forests, 13(6). https://doi.org/10.3390/f13060926

Walder, F., Schmid, M. W., Riedo, J., Valzano-Held, A. Y., Banerjee, S., Büchi, L., Bucheli, T. D., van der Heijden, M. G. A., 2022. Soil microbiome signatures are associated with pesticide residues in arable landscapes. Soil Biology and Biochemistry, 174, 108830. https://doi.org/10.1016/j.soilbio.2022.108830

Salicylic acid and its role in enhancing salt tolerance in crop plants

İlayda KULEYİN, Ayhan HORUZ *, Güney AKINOĞLU
Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Ayhan HORUZ
ayhanh@omu.edu.tr

Abstract

Soil salinity is a significant abiotic stress that severely impacts plant growth, development, and global agricultural productivity. As salinity levels rise, especially in irrigated regions, it increasingly endangers the viability of crops. Salt stress in plants primarily involves three key issues: osmotic stress, ionic toxicity, and oxidative damage. These factors collectively impede plant growth and lead to decreased agricultural yields. In response to these stresses, plants activate various defense mechanisms, with plant growth regulators (PGRs), such as salicylic acid (SA), playing a vital role in reducing these negative impacts. SA, a phenolic compound, functions as an endogenous signaling molecule that supports plants in overcoming salt stress by enhancing antioxidant defenses, regulating ion balance, and improving water and nutrient absorption. SA helps maintain cellular integrity by minimizing oxidative damage, stabilizing membranes, and optimizing the K^+/Na^+ ratio, which is crucial for osmotic regulation. Furthermore, SA stimulates the production of osmoprotectants like proline and glycine, which safeguard plant cells from dehydration and salt-induced harm. Studies have shown that the external application of SA can increase salt tolerance in crops such as Arabidopsis thaliana, maize, wheat, and barley by influencing physiological processes, including ion uptake, photosynthesis, and stress-related gene expression. However, the effectiveness of SA in improving salt tolerance is influenced by various factors, including the concentration applied, timing, and environmental conditions. Excessive amounts of SA may cause phytotoxicity, while inadequate doses might not yield significant benefits. Additionally, challenges such as environmental variability and cost factors may restrict the widespread use of SA in agricultural practices. Despite these challenges, exogenous SA application presents a promising approach to enhance plant resistance to salinity stress and reduce the detrimental effects of salinity on crop productivity. Future studies should aim to optimize the application techniques of SA and evaluate its effectiveness across a range of agricultural systems.

Keywords: Plant growth regulators, Salicylic acid, Salinity stress, Salt tolerance

Introduction

Plants are exposed to various environmental stresses, which can be broadly categorized into biotic stress (induced by living organisms) and abiotic stress (induced by non-living factors). While many stressors are present across different environments and climates, salinity stress, particularly in plants growing in arid and semi-arid regions, is a priority concern. Salinity stress is an abiotic factor that arises due to the accumulation of salts in the soil surrounding the plant roots, making the environment unsuitable for normal physiological functions and growth (Munns, 2005; Manchanda and Garg, 2008). Currently, around 1.1×10^9 hectares of land globally are affected by salinity, with the spread of saline soils accelerating at a rate of approximately 1.5 million hectares annually (Hossain, 2019). According to FAO estimates, salinity-induced degradation affects more than 6% of the world's land area, including nearly 20% of irrigated agricultural land (Parihar et al., 2015).

Salt stress triggers a series of physiological and biochemical responses in plants, leading to osmotic stress, ionic imbalance or toxicity, and oxidative damage. Osmotic stress impairs the plant's water absorption ability, which affects cellular growth and expansion. Ionic stress results from the harmful accumulation of ions like Na^+ and Cl^-, disrupting vital metabolic processes. Additionally, oxidative stress is caused by the excessive generation of reactive oxygen species (ROS), which can damage cell structures and macromolecules (García-Gómez et al., 2020).

To mitigate these stresses, plants employ several adaptive strategies. Among these, salicylic acid (SA), an endogenous plant growth regulator, plays a key role in reducing the detrimental effects of salinity stress (Gohari et al., 2020). SA enhances the plant's antioxidant defense system, maintains ion balance, and regulates various physiological functions, making it a promising approach for increasing salt tolerance in crops (Liu and Lal, 2015).

This study focuses on evaluating the role of salicylic acid in helping plants manage salt stress and enhancing their tolerance to salinity.

Salicylic Acid as a Plant Growth Regulator

Plant growth regulators (PGRs) are organic substances, either synthetically produced or naturally occurring, that influence various physiological processes in plants, even at very low concentrations (Rademacher, 2015). These compounds modulate plant growth and development by altering normal physiological functions (Rademacher, 2015). Some of the major PGRs include salicylic acid, nitric oxide, abscisic acid, auxins, cytokinins, brassinosteroids, gibberellins, jasmonates, and ethylene (Quamruzzaman et al., 2021).

Salicylic acid (SA), a phenolic compound, serves as a vital endogenous growth regulator in plants (Hayat et al., 2007). It plays a central role in regulating various physiological functions, such as ion uptake, nutrient transport, photosynthesis, stomatal regulation, and cellular respiration.

As a signaling molecule, SA helps plants respond to both biotic and abiotic stresses, including salt stress. By boosting antioxidant defense mechanisms, SA reduces oxidative damage induced by salt stress (Tabur et al., 2020). Furthermore, SA is involved in modulating ion absorption and transport, which is crucial for maintaining ion homeostasis in saline environments. This helps protect cellular integrity and minimizes the harmful effects of excessive Na^+ and Cl^- accumulation.

The Impact of Salicylic Acid on Plant Performance Under Saline Conditions

Salicylic acid (SA) plays a vital role in regulating plant responses to salt stress by influencing several physiological and biochemical pathways:

• **Ion Homeostasis**: The application of SA helps improve the K^+/Na^+ ratio in plants exposed to saline conditions, a critical factor for maintaining osmotic balance and ensuring normal cellular function (Kang et al., 2012).

• **Managing Oxidative Stress**: One of the primary ways in which SA alleviates salt-induced stress is by boosting the activity of antioxidant enzymes. It enhances the activities of peroxidase and catalase, enzymes responsible for neutralizing reactive oxygen species (ROS) and protecting plant cells from oxidative damage (Senaratna et al., 2000).

• **Accumulation of Osmoprotectants**: SA also stimulates the production of osmoprotectants like proline, betaine, and glycine. These compounds help maintain cellular structure and turgor pressure, which is crucial for plant survival under saline stress (Csiszár et al., 2020).

• **Regulation of Gene Expression**: Beyond promoting antioxidant activity and osmoprotectant synthesis, SA influences the expression of genes involved in the ascorbate-glutathione cycle, such as dehydroascorbate reductase (DHAR) and glutathione peroxidase (GPX), further enhancing the plant's ability to tolerate stress (Li et al., 2013).

Various crop species have been treated with SA to reduce the adverse effects of salt stress on growth, yield, and overall physiological performance. These include species like Brassica juncea, Arabidopsis thaliana, wheat, maize, barley, mung bean, Pennisetum giganteum, and Torreya grandis (Hayat et al., 2022; Torun et al., 2022). In these crops, SA application has proven to improve salt tolerance by enhancing processes such as ion balance, ROS scavenging, and the synthesis of protective compounds.

The Challenges and Limitations of Exogenous Salicylic Acid Application

While exogenous salicylic acid (SA) has demonstrated promise in improving salt tolerance, several challenges must be addressed to optimize its use under field conditions:

• **Concentration and Application Timing**: The efficacy of SA is significantly influenced by the concentration used and the time of its administration. Excessively high concentrations may cause phytotoxicity, while insufficient levels may fail to confer the desired protective effects.

• **Environmental Factors**: The efficacy of SA can vary under different environmental conditions, such as temperature, humidity, and soil composition, all of which can influence its uptake and activity within plants.

• **Cost and Accessibility**: The widespread application of exogenous SA in agricultural practices may be limited by its cost and the need for specialized application equipment, particularly in large-scale farming systems.

Despite these challenges, salicylic acid remains a valuable tool for mitigating salt stress, especially when used in combination with other agronomic practices.

Conclusion

SA is an effective plant growth regulator that plays a crucial role in enhancing plant tolerance to salinity stress. By improving ion homeostasis, reducing oxidative damage, and promoting the synthesis of protective compounds, SA can significantly enhance plant performance under salt-affected conditions. The external administration of SA presents a promising strategy to increase salt tolerance in crops, thus reducing the detrimental impacts of soil salinity on global agricultural productivity. However, the practical application of SA is still limited by factors such as optimal concentration, application timing, environmental conditions, and economic constraints. Further research is needed to optimize application methods and enhance the effectiveness of SA across diverse agricultural systems.

References

Csiszár, J., Brunner, S., Horváth, E., Bela, K., Ködmön, P., Riyazuddin, R., Gallé, Á., Hurton, Á., Papdi, C., Szabados, L., et al., 2018. Exogenously applied salicylic acid maintains redox homeostasis in salt-stressed Arabidopsis gr1 mutants expressing cytosolic roGFP1. Plant Growth Regul. 86, 181–194.

García-Gómez, C., Obrador, A., González, D., López, F., Fernández, M.D., 2020. Effect of cerium oxide nanoparticles on the growth, physiological responses, and ultrastructural changes of the halophyte Atriplex halimus L. under salt stress conditions. Environ. Sci. Pollut. Res. 27, 6293–6306.

Gohari, G., Zareei, E., Rostami, H., Panahirad, S., Kulak, M., Farhadi, H., Amini, H., 2021. Protective effects of cerium oxide nanoparticles in grapevine (Vitis vinifera L.) cv. Flame Seedless under salt stress conditions. Ecotoxicol. Environ. Saf. 220, 112402.

Hayat, K., Zhou, Y., Menhas, S., Hayat, S., Aftab, T., Bundschuh, J., Zhou, P., 2022. Salicylic acid confers salt tolerance in giant juncao through modulation of redox homeostasis, ionic flux, and bioactive compounds: An ionomics and metabolomic perspective of induced tolerance responses. J. Plant Growth Regul. 41, 1999–2019.

Hayat, S., Ali, B., Ahmad, A., 2007. Salicylic Acid: Biosynthesis, Metabolism and Physiological Role in Plants. In: Salicylic Acid: A Plant Hormone (pp. 1–14). Springer.

Hossain, M.S., 2019. Present scenario of global salt affected soils, its management and importance of salinity research. Int. Res. J. Biol. Sci. 1, 1–3.

Kang, G., Li, G., Zheng, B., Han, Q., Wang, C., Zhu, Y., Guo, T., 2012. Proteomic analysis on salicylic acid-induced salt tolerance in common wheat seedlings (Triticum aestivum L.). Biochim. Biophys. Acta Proteins Proteom. 1824, 1324–1333.

Li, G., Peng, X., Wei, L., Kang, G. 2013. Salicylic acid increases the contents of glutathione and ascorbate and temporally regulates the related gene expression in salt-stressed wheat seedlings. Gene, 529, 321–325.

Liu, Y., Cao, X., Yue, L., Wang, C., Tao, M., Wang, Z., Xing, B., 2022. Foliar-applied cerium oxide nanomaterials improve maize yield under salinity stress: Reactive oxygen species homeostasis and rhizobacteria regulation. Environ. Pollut. 299, 118900.

Manchanda, G., Garg, N., 2008. Salinity and its effects on the functional biology of legumes. Acta Physiol. Plant. 30, 595–618.

Munns, R., 2005. Genes and salt tolerance: Bringing them together. New Phytol. 167, 645–663.

Parihar, P., Singh, S., Singh, R., Singh, V.P., Prasad, S.M., 2015. Effect of salinity stress on plants and its tolerance strategies: A review. Environ. Sci. Pollut. Res. 22, 4056–4075.

Quamruzzaman, M., Manik, S.M.N., Shabala, S., Zhou, M., 2021. Improving performance of salt-grown crops by exogenous application of plant growth regulators. Biomolecules, 11(6), 788.

Rademacher, W., 2015. Plant growth regulators: Backgrounds and uses in plant production. J. Plant Growth Regul. 34, 845–872.

Senaratna, T., Touchell, D., Bunn, E., Dixon, K., 2000. Acetyl salicylic acid (aspirin) and salicylic acid induce multiple stress tolerance in bean and tomato plants. Plant Growth Regul. 30, 157–161.

Tabur, S., Avci, Z.D., Özmen, S., 2020. Exogenous salicylic acid application against mitodepressive and clastogenic effects induced by salt stress in barley apical meristems. Biologia, 76, 1–10.

Torun, H., Novák, O., Mikulík, J., Strnad, M., Ayaz, F.A., 2022. The effects of exogenous salicylic acid on endogenous phytohormone status in Hordeum vulgare L. under salt stress. Plants, 11, 618.

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

Assessment of USLE-K based on pythagorean fuzzy SWARA approach

Aykut CAGLAR [a,*], Orhan DENGIZ [b]
[a] Black Sea Agricultural Research Institute, Department of Soil and Water Resources, Samsun, Türkiye
[b] Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Aykut ÇAĞLAR
aykut.caglar@tarimorman.gov.tr

Abstract

Soil erosion is a serious issue that threatens soil in land degradation processes and to estimate the degree of soil erosion, the soil erodibility factor is an important instrument. This study aimed to compare different approaches in calculating the soil erodibility factor (USLE-K). In this context, the soil erodibility factor was calculated with 56 surface soil samples in an area susceptible to soil erosion in the Vezirköprü district of Samsun province, Türkiye. Alternatively, each parameter utilized in the soil erodibility factor was evaluated by expert opinion, and the soil erodibility factor was determined using the Pythagorean Fuzzy Swara method (PF-SWARA-K). Within the scope of the study, sand, clay, silt, organic matter, structural stability index, and hydraulic conductivity values of the soils were examined. In the results obtained by evaluating the expert opinions and using the Pythagorean Fuzzy SWARA approach, the values of organic matter, clay, structure stability index, hydraulic conductivity, silt, and sand were 0.443, 0.229, 0.129, 0.092, 0.058, 0.048, respectively. The standard scoring function was used to standardize the criteria values using a linear function. In the results, it is seen that the USLE-K values obtained with traditional methods and the PF-SWARA-K values determined with the Pythagorean Fuzzy SWARA approach have a significant relationship with 0.768 at the 1% level. These results obtained with this study show that multi-criteria decision-making methods can be used in determining the soil erodibility factor.

Keywords: GIS, Pythagorean fuzzy SWARA, Soil erodibility, USLE-K

Introduction

The soil erodibility factor (K factor) is a basic parameter that determines the susceptibility of a soil to erosion and is widely used in erosion models. This factor is affected by the physical and chemical properties of the soil; it is especially associated with properties such as soil texture, permeability, organic matter content and particle size (Wischmeier and Smith, 1978; Renard et al., 1997). The soil erodibility factor is a key component of the Universal Soil Loss Equation (USLE), which is widely used to determine the rate of soil erosion. An accurate estimate of the K factor helps to predict soil erosion more reliably (Oda et al, 2021, Plambeck, 2020). The K factor, along with soil aggregate stability, is used to assess soil degradation under different land-use changes. It helps in identifying areas at higher risk of erosion and implementing appropriate conservation measures (Jiang et al, 2020, Ferreria, 2015).

Multi-criteria decision-making (MCDM) methods have become popular in many studies in spatial planning and management disciplines and are considered a useful tool for researchers, especially in the context of multi-factor evaluations (Valkanou et al., 2021). It is widely used in determining soil erosion risk areas (Demirağ Turan and Dengiz, 2017, Olii et al, 2024), the priorities of sub-basins (Bhattacharya et al., 2020, Jaman et al., 2024), site suitability areas (Özkan et al., 2019, Otgonbayar et al., 2017), and soil quality studies (Dengiz and Turan, 2023, Kaya et al., 2022).

Yager (2013) advanced the concept of Pythagorean Fuzzy Sets (PFSs) as part of the ongoing development in the field of MCDM. PFSs are characterized by the requirement that the sum of the squared membership and non-membership degrees must remain less than or equal to 1. This framework provides decision-makers with the ability to assess options from a more comprehensive perspective. The SWARA method, introduced by Keršulienė et al. (2010), facilitates the assignment of criteria weights by incorporating the priority rankings established by decision-makers. The Pythagorean Fuzzy SWARA method has been widely applied in recent years to address multi-criteria decision-making problems, yielding effective results in various contexts. For instance, Rani et al. (2020) utilized the Pythagorean Fuzzy SWARA–VIKOR framework to evaluate the performance of solar panel selection. Similarly, Saraji et al. (2021) applied the Pythagorean Fuzzy SWARA-TOPSIS framework to assess the progress of the European Union in sustainable energy development. Additionally, Chaurasiya and Jain (2024) employed the Pythagorean Fuzzy MEREC-SWARA-ARAS method to evaluate the adoption of IoT technologies in waste management for smart cities. These studies demonstrate the method's broad applicability and its ability to enhance decision-making processes.

This study aimed to compare different approaches in calculating the soil erodibility factor (USLE-K). In this context, the soil erodibility factor was calculated with surface soil samples in an area susceptible to soil erosion in the Vezirköprü district of Samsun province, Türkiye. Alternatively, each parameter utilized in the soil erodibility factor was evaluated by expert opinion, and the soil erodibility factor was determined using the Pythagorean Fuzzy Swara method (PF-SWARA-K).

Material and Methods

Study Area

The study area is situated in the Vezirköprü district, located in the southern part of Samsun Province, and spans a total of 601.82 decares (Figure 1). The terrain is predominantly steep. The area experiences a blend of Black Sea and continental climate characteristics, resulting in colder winters and hotter summers compared to the coastal regions. Based on long-term meteorological data, the annual average precipitation is 724.5 mm, while the average temperature is 12.5 °C. According to the Newhall simulation model, the soils in the study area are classified with a Mesic soil temperature regime and a Xeric soil moisture regime (Van Wambeke, 2000; Turan et al., 2018).

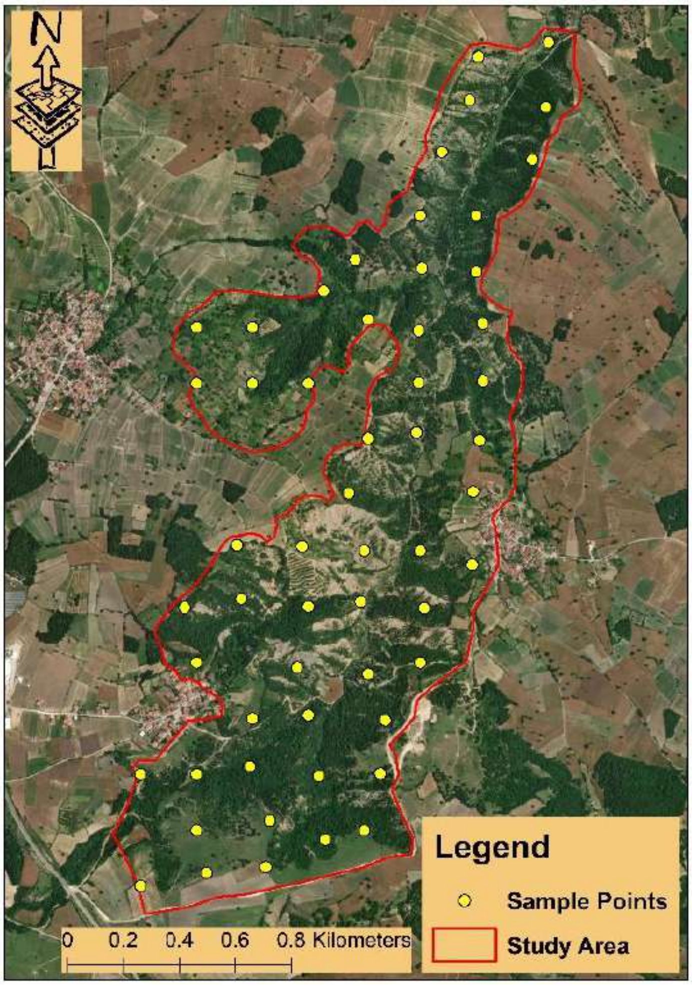


Figure 1. Location map of the study area

Soil sampling and analysis

As part of the study, fifty-six surface soil samples were collected from the study site. The samples we taken from a depth of 0 – 30 cm. The study employed the Bouyoucos (1962) method to analyze soil texture, the Walkley-Black method (Jackson, 1958) to assess organic matter content, the Klute and Dirksen (1986) method to measure hydraulic conductivity. In parts when organic matter is greater than 4% is limited to 4% because of the calculation of USLE-K. Based on these analyses, the USLE-K factor was calculated, and soil structure classes were identified following the classification by Wischmeier and Smith (1978).

Soil Erodibility

The equation related to soil erodibility USLE-K factor is given below (Equation 1).

$K = 1/100 \{2.1 \times 10{-}4 \times (12 - OM) \times [SI \times (SA + SI)]1.14 + 2.5 \times (PE - 3) + 3.25 \times (ST - 2)\}$ (1)

K: Soil erodibility (t ha h ha-1 MJ mm-1), OM: Soil organic matter, SI: silt content, SA: sand content, PE: permeability class, ST: structure code.

Pythagorean fuzzy set theory preliminary definition

Pythagorean Fuzzy Sets (PFSs) were first introduced by Yager (Yager, 2013) in 2013 and were developed as an extension of Intuitive Fuzzy Sets (IFSs) to offer decision makers a wider scope in defining uncertainties. When determining Intuitive Fuzzy Sets, the sum of the membership and non-membership degrees cannot be greater than 1, but when defining uncertainty in PFSs, the sum of the squares of the membership and non-membership degrees is determined to not exceed 1. This condition enables PFSs to cover a much wider area in defining uncertainties.

The following equations are used to define PFSs (Yager, 2013).

$P = \{x, \mu_p(x), v_p(x); x \in X\}$ (2)

Here, μ_p: X $\longrightarrow$ [0,1] defines with the degree of membership, v_p : X $\longrightarrow$[0,1] defines with the degree of non-membership.

$0 \leq (\mu_p(x))^2 + (v_p(x))^2 \leq 1$ (3)

To determine the hesitation degrees of PFSs.

$\pi p(x) = \sqrt{1- (\mu_p(x))^2+(v_p(x))^2}$ (4)

Arithmetic operations for $\beta_1 = P(\mu_{\beta 1}, v_{\beta 1})$ ve $\beta_2 = P(\mu_{\beta 2}, v_{\beta 2})$

$\beta_1 \oplus \beta_2 = P(\sqrt{\mu_{\beta 1}^2 + \mu_{\beta 2}^2 - \mu_{\beta 1}^2 \mu_{\beta 2}^2}, v_{\beta 1} v_{\beta 2}$ (5)

$\beta_1 \otimes \beta_2 = P(\mu_{\beta 1} \mu_{\beta 2}, \sqrt{v_{\beta 1}^2 + v_{\beta 2}^2 - v_{\beta 1}^2 v_{\beta 2}^2})$ (6)

$\lambda\beta = P(\sqrt{1 - (1 - \mu_\beta^2)^\lambda}, (v_\beta)^\lambda)$ (7)

$\beta^\lambda = P((\mu_\beta)^\lambda, \sqrt{1 - (1 - v_\beta^2)^\lambda})$ (8)

To determine the score and uncertainty functions of PFSs are (Zhang ve Xu, 2014);

$S(\beta) = (\mu_\beta)^2 - (v_\beta)^2, \hbar(\beta) = (\mu_\beta)^2 + (v_\beta)^2$, here, $S(\beta) \in [-1, 1]$ ve $\hbar(\eta) \in [0, 1]$. (9)

Here, since the score (S) function is between [- 1, 1], equation 10 is used when calculating the normalized form of the values and the degree of uncertainty. (Wu ve Wei, 2017).

$S^*(\beta) = \frac{1}{2}(S(\beta)+1), \hbar^\circ(\beta) = 1 - \hbar(\beta)$, thus, $S^*(\beta), \hbar^\circ(\beta) \in [0, 1]$. (10)

Pythagorean fuzzy swara approach

The steps of using the pythagorean fuzzy swara approach are as follows;

Step 1: First, experts are rated using the scale in Table 1, taking into account their work history and expertise on the subject.

Table 1. Scale for evaluating the performance of experts

Linguistic expressions	Pythagorean Fuzzy Numbers (μ, v, π)
Extremely important (EI)	(0.90, 0.15, 0.409)
Very very important (VVI)	(0.75, 0.40, 0.527)
Very important (VI)	(0.70, 0.55, 0.456)
Important (I)	(0.60, 0.70, 0.387)
Less important (LI)	(0.40, 0.80, 0.447)
Very less important (VLI)	(0.30, 0.90, 0.316)

Step 2: The following equation (Equation 11) is used to calculate the weights of experts. Here, let Ek=γ("μ" _k,"v" _k) be in the Pythagorean fuzzy set of k experts, while calculating the weight of this expert;

$$\omega_k = \frac{(\mu_k^2+\pi_k^2\times(\frac{\mu_k^2}{\mu_k^2+v_k^2}))}{\sum_{k=1}^{\ell}(\mu_k^2+\pi_k^2\times(\frac{\mu_k^2}{\mu_k^2+v_k^2}))}, k = 1(1)\ell; \omega_k \geq 0, \sum_{k=1}^{\ell}\omega_k = 1. \quad (11)$$

Step 3: The criteria are ranked from highest to lowest according to their importance, taking into account expert opinions. Here, the criteria are ranked according to their importance in line with expert opinions before pairwise comparisons.

Step 4: At this stage, normalized score function values were obtained by making a pairwise comparison of the criteria determined according to their importance level with the criterion in the lower row. Although it is similar to the traditional SWARA method in terms of method, The linguistic expressions used by experts to evaluate the criteria within the scope of the study are listed in Table 2.

Table 2. Linguistic expressions used for expert opinions (Saeidi ve ark., 2022)

Linguistic expressions	Pisagor Bulanık Sayılar (μ, v, π)
Absolutely high (AH)	(0.95, 0.20, 0.387)
Very very high (VVH)	(0.85, 0.30, 0.433)
Very high (VH)	(0.80, 0.35, 0.487)
High (H)	(0.70, 0.45, 0.554)
Medium high (MH)	(0.60, 0.55, 0.581)
Medium (M)	(0.50, 0.60, 0.624)
Medium low (ML)	(0.40, 0.70, 0.592)
Low (L)	(0.30, 0.75, 0.589)
Very low (VL)	(0.20, 0.85, 0.487)
Absolutely low (AL)	(0.10, 0.95, 0.296)

Step 5: At this stage, the most important criterion in calculating the Kj value is determined as 1, and +1 is added to each score value below it (Equation 12) (Kerŝulienė et al., 2010).

$$kj = \begin{cases} 1 & ,j = 1 \\ Sj+1 & ,j > 1 \end{cases} \quad (12)$$

Step 6: In this step, the importance vector is calculated and, as stated in the previous equation, the most important criterion is 1, and the importance vectors for other criteria are determined by dividing the previous importance vector to the criterion coefficient (Equation 13).

$$q_j = \begin{cases} 1 & j = 1 \\ \frac{q(j\text{-}1)}{kj} & ,j > 1 \end{cases} \quad (13)$$

Step 7: The final weights of the criteria are obtained by dividing the weight of the importance vectors obtained in the previous step by the sum of the importance vector weights as stated in Equation 14. The m value here represents the number of criteria.

$$Wj = \frac{qj}{\sum_{j=1}^{m} qj} \quad (14)$$

Step 8: Within the scope of the study, the criterion weights in the study are calculated for each expert by following the above steps. In the next stage, the sum of the values obtained by multiplying the expert weights obtained within the scope of evaluating the experts and the criterion weights obtained from the experts is taken and the criterion weights are calculated.

Standard scoring function

Accounting for differences in soil parameter units, the standard scoring function was applied to normalize the values, assigning scores between 0 and 1 (Andrews et al., 2002). This scoring function allows for the assessment of low, high, and average levels of the desired characteristics within the study's context (Liebig et al., 2001). Two distinct scoring functions were employed to establish a linear relationship between the score values used in estimating soil erodibility and the soil erodibility calculated using the formula developed by Wischmeier and Smith (1978). The "Less is Better" (LB) function was used for organic matter content, clay content, structural stability, and soil permeability values. Conversely, the "More is Better" (MB) function was applied for sand and silt properties (Table 3).

Table 3. Standard Scoring Functions for parameters

Parametreler	Skor Fonksiyonu	L	U	Standart Skorlama Fonksiyonu Eşitliği
Organic Matter	LB	0.18	4.00	$f(x) = \begin{cases} 0.1 & ,x \leq L \\ (1 - (0.9) * (\frac{x-L}{U-L})), & L \leq x \leq U \\ 1 & ,x \geq U \end{cases}$ (15)
Clay	LB	15.81	51.91	
Structure Degree	LB	2.00	4.00	
Hydraulic Conductivity	LB	0.14	2.73	
Silt	MB	15.24	41.15	$f(x) = \begin{cases} 0.1 & ,x \leq L \\ (0.1 + (0.9) * (\frac{x-L}{U-L})), & L \leq x \leq U \\ 1 & ,x \geq U \end{cases}$ (16)
Sand	MB	17.56	63.83	

After determining the weights for the relative importance of soil erodibility parameters using PF-SWARA method and obtaining normalized values through the standard scoring function, the Weighted Linear Combination (WLC) method was applied to assess soil erodibility levels (Eq. 17).

$$\text{PF\_SWARA} - \text{K} = \sum_{k=1}^{\ell} \omega_k * a_{ik} \quad (17)$$

Here, ω_k represents the criteria weights, a_{ik} is the normalized standard value of the parameters.

Results And Discussion

The parameters used to calculate USLE-K and PF-SWARA-K values were given in table 4 for descriptive analysis. It is observed that the % clay contents vary between 15.81% and 51.91%, % sand contents vary between 17.56% and 63.83% and % silt contents vary between 15.24% and 41.15%. The soils' organic matter content ranges between 0.18 and 4.00. While traditional USLE-K values ranges between 0.07 and 0.26, PF-SWARA-K values vary between 0.39 and 0.75 respectively.

Table 4. Descriptive statistics values

	Mean	Minimum	Maximum	Std. Deviation	Variance	Skewness	Kurtosis
USLE-K	0,15	0,07	0,26	0,05	0,00	0,49	-0,48
PF_SWARA-K	0,54	0,39	0,75	0,10	0,01	0,40	-1,13
Sand	39,40	17,56	63,83	12,40	153,85	0,30	-0,96
Clay	32,07	15,81	51,91	8,48	71,94	-0,11	-0,64
Silt	28,53	15,24	41,15	5,56	30,90	-0,26	-0,44
Organic Matter	2,83	0,18	4,00	1,22	1,48	-0,59	-0,97
Structure Degree	2,34	2,00	4,00	0,61	0,37	1,64	1,63
Hydraulic Conductivity	0,78	0,14	2,73	0,66	0,44	1,51	1,65

SD: standard deviation, Min.: minimum, Max.: maximum, n: sample number (78),
CV (coefficient of variation): <15 = low variation, 15–35 = moderate variation, >35 = high variation
Skewness:< │ +- 0.5 │ = normal distribution, 0.5–1.0 = application of character changing for dataset, and >1.0 → application of Logarithmic change

In this study, pairwise comparisons between the USLE-K values from actual measurements and the K factor calculated using PF-SWARA method in table 5. A statistically significant correlation of 0.768** ($p < 0.01$) between the soil erodibility factor calculated by the PF-SWARA method and the USLE-K method highlights the effectiveness of the applied approach. Rather than focusing on pairwise comparisons of all parameters, it would be more appropriate to analyze the significance of the criteria used in calculating soil erodibility in the context of PF-SWARA-K and USLE-K.

Table 5. Correlation values between model outputs

	USLE-K	PF_SWARA-K
USLE-K	1,000	
PF_SWARA-K	0,768**	1,000

*Correlation is significant at 0.05.
**Correlation is significant at 0.01 level.

Weighting of soil Erodibility criteria by PF-SWARA

Within the scope of the study, weight determination studies were carried out in line with expert opinions of six parameters calculated in the USLE-K formula for determining the soil erodibility factor. In this context, three researchers who are experts in the field were determined and the stages of the PF-SWARA method were presented to each expert for evaluation. First of all, each expert was evaluated and Table 1 was used in the evaluation of the experts. As a result of the study, the weights of the experts were found to be 0.372, 0.372 and 0.255, respectively.

Table 6. Calculation of criterion weights according to expert 1 opinion and final weights

Parameters	Expert1 (μ, ν)	sj*	kj	pj	Weights
Organic Matter			1,000	1,000	0,449
Clay	(0.95, 0.20)	0,931	1,931	0,518	0,233
Structure Degree	(0.80, 0.35)	0,759	1,759	0,294	0,132
Hydraulic Conductivity	(0.50, 0.60)	0,445	1,445	0,204	0,092
Silt	(0.85, 0.30)	0,816	1,816	0,112	0,050
Sand	(0.20, 0.85)	0,159	1,159	0,097	0,044

Sj: the comparative significance of score value, kj: relative coefficient, qj: the weight of the importance vector, Wj: the final weight of criteria.

Within the scope of the study, only the calculation results of one of the experts were given in detail (Table 6). Each expert was asked to rank the criteria for determining the soil erodibility factor according to their importance. According to the obtained results, Organic Matter, Clay, Structure Degree, Hydraulic Conductivity, Silt, and Sand were ranked according to their importance and the total weights of the experts were calculated as 0.443, 0.229, 0.129, 0.092, 0.058, and 0.048 respectively. The results show that according to expert opinions, organic matter is the most important criterion in determining the soil erodibility factor, followed by clay and structural degrees of soils.

Table 7. Final weights of the parameters of PF-SWARA-K

Parameters	Expert 1	Expert 2	Expert 3	Final Weights
Organic Matter	0,449	0,434	0,446	0,443
Clay	0,233	0,225	0,231	0,229
Structure Degree	0,132	0,128	0,127	0,129
Hydraulic Conductivity	0,092	0,096	0,088	0,092
Silt	0,050	0,066	0,058	0,058
Sand	0,044	0,052	0,050	0,048

Spatial distributions of soil erodibility factor

In this study, distribution maps were created as a result of the calculations of the soil erodibility of USLE-K and the PF-SWARA-K method, which we weighed with the soil erodibility parameters calculated with the Pythagorean fuzzy SWARA approach and then determined with the standard scoring function. When the correlation values of the soil erodibility factor calculated with both methods within the scope of the study are examined, it is seen that significant results were obtained 0.768** ($p < 0.01$) in the Pearson correlation test. When we look at the distribution maps, we see the existence of sensitive areas considered high risk in the central parts of the study area. It is seen that less sensitive areas are distributed in parallel in the southern parts of the study in both methods.

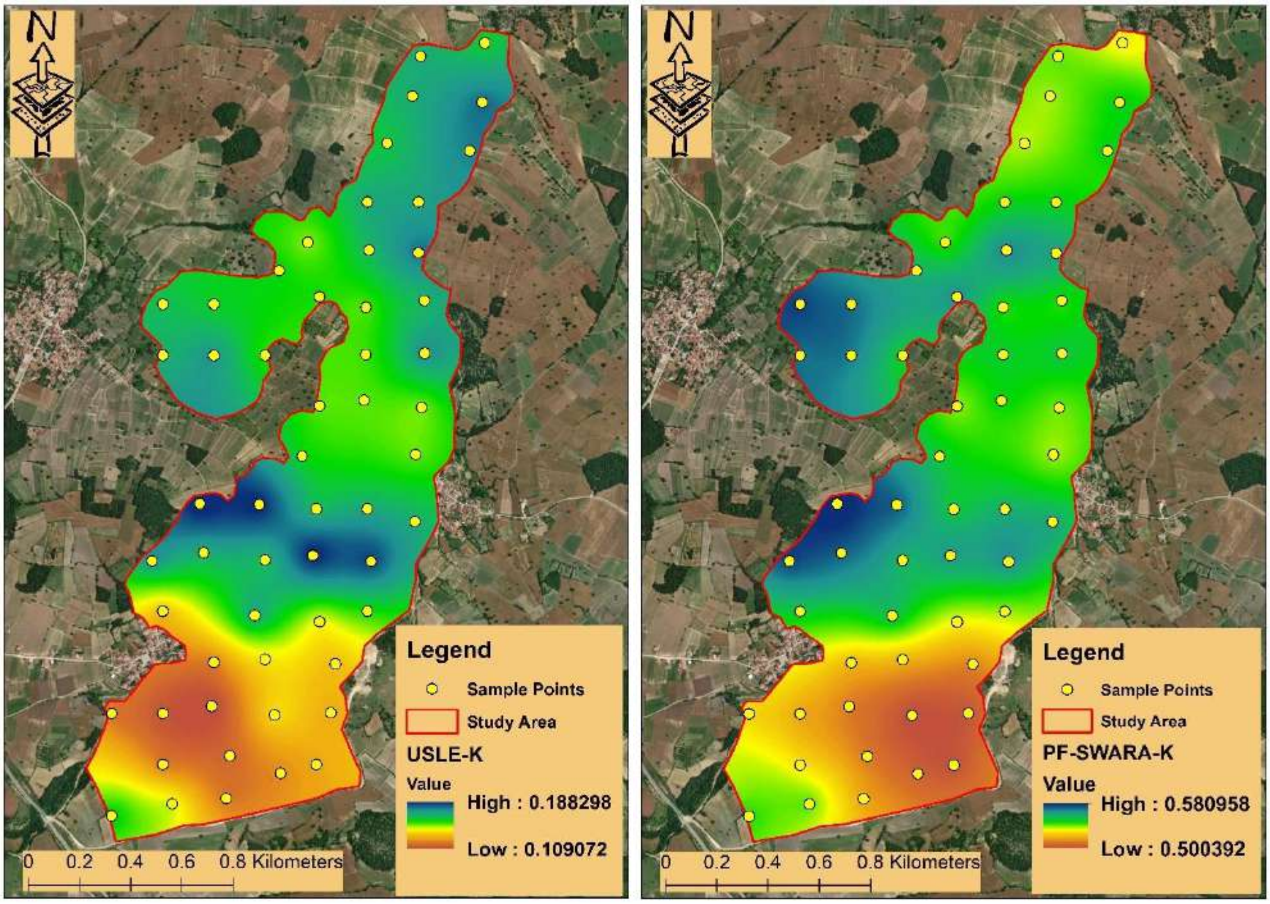


Figure 2. Distribution maps of USLE-K and PF-SWARA-K

Conclusion

Soil erosion is a serious issue that threatens soil in land degradation processes and to estimate the degree of soil erosion, the soil erodibility factor is an important instrument. This study is a comparison of the results obtained from USLE-K and Pythagorean fuzzy SWARA-K method in determining soil erodibility. For this purpose, each parameter used in determining soil erodibility was also used in the Pythagorean fuzzy SWARA approach and the weights of each parameter were obtained.

As a result of the study, we obtained by evaluating the expert opinions and using the Pythagorean Fuzzy SWARA approach, the values of organic matter, clay, structure stability index, hydraulic conductivity, silt, and sand were 0.443, 0.229, 0.129, 0.092, 0.058, 0.048, respectively. It is seen that the USLE-K values obtained with traditional methods and the PF-SWARA-K values determined with the Pythagorean Fuzzy SWARA approach have a significant relationship with 0.768 at the 1% level. These results obtained with this study show that multi-criteria decision-making methods can be used in determining the soil erodibility factor and It may be possible to get better results with some improvements and perhaps a higher sample size and expert diversity.

References

Andrews, S.S., Karlen, D.L, Mitchell, J.P., 2002. A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agri Ecosyst Environ*. 90:25–45. doi:10.1016/S0167-8809(01)00174-8.

Bhattacharya, R. K., Chatterjee, N. D., Das, K., 2020. Sub-basin prioritization for assessment of soil erosion susceptibility in Kangsabati, a plateau basin: a comparison between MCDM and SWAT models. *Science of the Total Environment*, *734*, 139474.

Bouyoucos, G. J., 1962. Hydrometer method improved for making particle size analyses of soils 1. *Agronomy journal*. 54(5): 464-465.

Chaurasiya, R., Jain, D., 2024. IoT Adoption for Smart Cities Waste Management using Pythagorean Fuzzy MEREC-SWARA-ARAS Method. *Proc. Natl. Acad. Sci., India, Sect. A Phys. Sci.* (2024). https://doi.org/10.1007/s40010-024-00902-x

Demirağ Turan, İ., Dengiz, O., 2017. Çok Kriterli Değerlendirme ile Ankara Güvenç Havzası'nda Erozyon Risk Tahminlenmesi. *Journal of Agricultural Sciences*, 23(3), 285-297.

Dengiz, O., Demirağ Turan, İ., 2023. Soil quality assessment for desertification based on multi-indicators with the best-worst method in a semi-arid ecosystem. *Journal of Arid Land*, *15*(7), 779-796.

Ferreira, V., Panagopoulos, T., Andrade, R., Guerrero, C., Loures, L., 2015. Spatial variability of soil properties and soil erodibility in the Alqueva reservoir watershed. *Solid Earth*, 6, 383-392. https://doi.org/10.5194/SE-6-383-2015.

Jackson, M.L., 1958. Soil Chemical Analysis. Prentice Hall Inc., Englewood Cliffs, N.J.

Jaman, M. H., Das, S., Chatterjee, J., Roy, S., Sengupta, S., 2024. Sub-basin prioritisation from morphometry for erosion management in an undulating rocky terrain: Validating different MCDM techniques with respect to RUSLE in the Chaka River Basin, Eastern India. *Journal of Earth System Science*, *133*(3), 119.

Jiang, Q., Zhou, P., Liao, C., Liu, Y., Liu, F., 2020. Spatial pattern of soil erodibility factor (K) as affected by ecological restoration in a typical degraded watershed of central China.. *The Science of the total environment*, 749, 141609. https://doi.org/10.1016/j.scitotenv.2020.141609.

Kamali Saraji, M., Streimikiene, D. Ciegis, R.A., 2022. Novel Pythagorean fuzzy-SWARA-TOPSIS framework for evaluating the EU progress towards sustainable energy development. *Environ Monit Assess* **194**, 42 (2022). https://doi.org/10.1007/s10661-021-09685-9

Kaya, N. S., Özkan, B., Dengiz, O., Turan, İ.D., 2022. Digital mapping and spatial variability of soil quality ındex for desertification in the Akarçay Basin under the semi-arid terrestrial ecosystem using neutrosophic fuzzy-AHP approach. *Natural Hazards*, *112*(3), 2101-2132.

Keršulienė, V., Zavadskas, E. K., Turskis, Z., 2010. Selection of rational dispute resolution method by applying new step-wise weight assessment ratio analysis (Swara). *Journal of Business Economics and Management*, 11(2), 243-258. https://doi.org/10.3846/jbem.2010.12

Klute, A., Dirksen, C., 1986. Hydraulic conductivity and diffusivity: Laboratory methods. *Methods of soil analysis: Part 1 physical and mineralogical methods*. 5: 687-734.

Liebig, M.A., Varvel, G., Doran, J., 2001. A simple performance-based ındex for assessing multiple agroecosystem functions. *Soil and Crop Management*. 93(2): 313-318.

Oda, M., Nwe, Y., Omae, H., 2021. Locally measured USLE K factor expands sustainable agricultural land in Palau.. F1000Research, 9, 89 . https://doi.org/10.12688/f1000research.22229.3.

Olii, M. R., Olii, A. K. Z., Olii, A., Pakaya, R., Kironoto, B.A., 2024. Spatial modeling of soil erosion risk: a multi-criteria decision-making (MCDM) approach in the paguyaman watershed, gorontalo, Indonesia. *Arabian Journal of Geosciences*, *17*(7), 226.

Otgonbayar, M., Atzberger, C., Chambers, J., Amarsaikhan, D., Böck, S., Tsogtbayar, J., 2017. Land suitability evaluation for agricultural cropland in Mongolia using the spatial MCDM method and AHP based GIS. *Journal of Geoscience and Environment Protection*, *5*(9), 238-263.

Özkan, B., Dengiz, O., & Demirağ Turan, İ., 2019. Site suitability assessment and mapping for rice cultivation using multi-criteria decision analysis based on fuzzy-AHP and TOPSIS approaches under semihumid ecological condition in delta plain. *Paddy and Water Environment*, *17*, 665-676.

Plambeck, N., 2020. Reassessment of the potential risk of soil erosion by water on agricultural land in Germany: Setting the stage for site-appropriate decision-making in soil and water resources management. *Ecological Indicators*, 118, 106732. https://doi.org/10.1016/j.ecolind.2020.106732.

Rani, P., Mishra, A. R., Mardani, A., Cavallaro, F., Štreimikienė, D., Khan, S.A.R., 2020. Pythagorean Fuzzy SWARA–VIKOR Framework for Performance Evaluation of Solar Panel Selection. *Sustainability*, *12*(10), 4278. https://doi.org/10.3390/su12104278

Renard, K.G., Foster, G.R., Weesies, G. A., McCool, D. K., Yoder, D.C., 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). *USDA Agriculture Handbook* 703. USDA, Washington, DC, USA.

Saeidi, P., Mardani, A., Mishra, A.R., Cajas, V.E.C., Carvajal, M.G,. 2022. Evaluate sustainable human resource management in the manufacturing companies using an extended Pythagorean fuzzy SWARA-TOPSIS method. *Journal of Cleaner Production*, 370, 133380.

Turan, M., Dengiz, O., Turan, İ.D., 2018. Samsun ilinin Newhall modeline göre Toprak sıcaklık ve nem rejimlerinin belirlenmesi. Türkiye Tarımsal Araştırmalar Dergisi, 5(2), 131- 142.

Valkanou, K., Karymbalis, E., Papanastassiou, D., Soldati, M., Chalkias, C., Gaki-Papanastassiou, K., 2021. Assessment of Neotectonic Landscape Deformation in Evia Island, Greece, Using GIS-Based Multi-Criteria Analysis. *ISPRS Int. J. Geo.-Inf.* , 10, 118.

Van Wambeke, A.R., 2000. The Newhall Simulation Model for estimating soil moisture & temperature regimes. Department of Crop and Soil Sciences. Cornell University, Ithaca, NY.

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses. *USDA*, Washington, DC, USA.

Wu, S.J., Wei, G.W., 2017. Pythagorean fuzzy hamacher aggregation operators and their application to multiple attribute decision making. *Int. J. Knowledge-based Intell. Eng. Syst.* 21, 189–201.

Yager, R.R., 2013. Pythagorean membership grades in multicriteria decision making. *IEEE Transactions on Fuzzy Systems*, 22(4), 958–965.

Zhang, X., Xu, Z., 2014. Extension of TOPSIS to multiple criteria decision making with pythagorean fuzzy sets. *Int. J. Intell. Syst*. 29 (12), 1061–1078. https://doi.org/ 10.1002/int.21676.

Application of pedotransfer functions and machine learning for soil bulk density modelling

Baig Abdullah Al SHOUMIK [1,2,*], Coşkun GÜLSER [2]

[a] Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Turkey
[b] University of Agriculture in Krakow, Department of Soil Science and Soil Protection, Kraków, Poland

***Corresponding Author**

Baig Abdullah Al SHOUMIK
baig.munim53@gmail.com

Abstract

Soil bulk density (D_b) is an important soil physical property that influences soil health, carbon storage, nutrient stock, and agricultural productivity. Despite its importance, the traditional methods for measuring D_b, such as volume-core sampling and laboratory analysis, are labor-intensive, expensive, and impractical for large-scale assessments. To overcome these limitations, researchers have developed predictive tools, including pedotransfer functions (PTFs) and machine learning (ML) models, leveraging auxiliary soil properties to estimate D_b efficiently. PTFs are often region-specific and limited in capturing complex interactions among variables. In contrast, ML models, such as random forests, artificial neural networks, and support vector machines, excel in handling large datasets and intricate nonlinear relationships, producing more accurate predictions at broader scales. This paper explores the use of pedotransfer functions and machine learning algorithms as effective alternatives for predicting D_b based on auxiliary soil properties such as organic matter, texture, and pH. PTFs, though efficient, often exhibit region-specific limitations, while ML algorithms provide enhanced predictive capabilities by capturing complex, nonlinear relationships. This review highlights the current advancements of D_b modeling, emphasizing the advantages and challenges of both approaches for precise predictions and enhance the prediction accuracy across diverse soils and regions.

Keywords: Bulk density modelling; Machine learning; Pedotransfer functions

Introduction

Soil bulk density (D_b) is defined by the dry soil mass per unit volume of soil under the natural conditions. This is one of the most important soil physical properties as it is associated with porosity, structure, biological activities, infiltration rate, available water holding capacity, nutrient stock (including soil organic carbon stock), root growth, etc. (Wang et al., 2024; Abdelbaki, 2016; Han et al., 2016). Dry soil bulk density along with porosity are frequently used as robust indicators to the degree of soil compaction (Håkansson and Lipiec, 2000). However, determining D_b by field sampling and laboratory procedure is a laborious, expensive, and time-consuming task, especially when it is about a large-scale area (Chen et al., 2018; Yi et al., 2016; Sequeira et al., 2014). Even in some cases, volume-core sampling method becomes difficult due to the presence of roots and rocks in high amount (Abdelbaki, 2016).

Scientists have developed numerous pedotransfer functions (PTFs) to predict approximate D_b values based on empirical formulas from available information. The PTFs have made it very easy to predict bulk density using easily obtainable soil properties, such as soil particles, SOC, pH, topography, land use, etc. (Nanko et al., 2014; Sequeira et al., 2014; Han et al., 2012). These functions are very effective for predicting D_b for a large area. However, the performance of the developed PTFs varies depending on regions, climates, and land uses since they have different soil types (Palladino et al., 2022). For instance, the PTF developed by Reis et al., (2024) for predicting D_b in Brazil will less likely to have better prediction for other regions. Machine learning (ML) is another advanced approach that is widely applied in soil science research for predicting different soil properties. Like PTFs, machine learning algorithms consider different variables. However, it captures intricate relationship between the targeted variables and auxiliary variables for the prediction. Some of the most common machine learning techniques are artificial neural networks (ANN), random forest (RF), k-nearest neighbor (k-NN), gradient boosting regression, linear or additive models, etc (Palladino et al., 2022; Sequeira et al., 2014). A well-developed and precise D_b model through PTF and ML approaches can ease to evaluate the carbon and nutrient stock for a large area, even at the continental-scale. This review summarizes the application of PTFs and machine learning algorithms for soil D_b modelling.

Pedotransfer functions to predict soil bulk density

Pedotransfer functions (PTFs) are mathematical models or empirical relationships used to estimate soil properties that are challenging or expensive to measure directly, such as bulk density, hydraulic conductivity, and water retention, based on more easily measured soil attributes like texture, organic matter, and bulk density itself. Modern advancements in pedotransfer functions leverage machine learning, data fusion, and probabilistic frameworks to enhance predictive accuracy and capture uncertainty.

Pedotransfer functions predict bulk density based on its relationship with other soil properties, such as organic matter, texture, porosity, etc. These functions are mostly empirical equations developed from the statistical relationship among the variables. These equations vary from region to region due to different soil type. For instance, Abdelbaki (2016) analyzed the predictive accuracy of around 48 PTFs developed by numerous scientists across the world, and he found 8 PTFs that revealed the best performance with the root mean square error (RMSE) of <0.18 (Eq. 1-8) (Table 1), while 7 PTFs had moderate performance with RMSE<0.2, and 9 showed poor performance (RMSE>0.24) for predicting bulk density. However, he revealed a new PTF that outperformed the other equations revealing the RMSE of 0.13 (Eq. 9). Most of these empirical equations are based on soil organic matter (SOM) and soil texture (e.g. particles).

Table 1. Best PTFs for soil bulk density modelling. (Source: Abdelbaki, 2016).

PTF equations	Eq. number	RMSE	ME	References
$BD = 1.66 - 0.308(OC)^{0.5}$	1	0.16	-0.01	Alexander (1980)
$BD = 1.72 - 0.294(OC)^{0.5}$	2	0.17	0.06	
$BD = 1.66 - 0.318(OC)^{0.5}$	3	0.16	-0.01	Manrique and Jones (1991)
$BD = 0.159 \times 1.561/[1.561 \times \frac{OM}{100} + 0.159\left(1 - \frac{OM}{100}\right)]$	4	0.16	-0.02	Prévost (2004)
$BD = 1.5224 - 0.0005 \times Clay$	5	0.16	-0.01	Benites et al., (2007);
$BD = (2.684 - 140.943 \times 0.006) \times Exp[-(0.006 \times OC)]$	6	0.15	0.04	Ruehlmann and Körschens (2009)
$BD = 0.167 \times 1.526/[1.526 \times \frac{OM}{100} + 0.167\left(1 - \frac{OM}{100}\right)]$	7	0.16	-0.04	Han et al., (2012)
$BD = 0.69794 + 0.750636 \times Exp(-0.230355 \times OC) + (0.0008687 \times Sand) - (0.0005164 \times Clay)$	8	0.16	-0.06	Hollis et al., (2011)
$BD = 1.449e^{-0.03 \times OC}$	9	0.13	0	Abdelbaki (2016)

Machine learning algorithms to predict soil bulk density

Machine learning algorithms such as neural networks or random forest to predict D_b often produces better result as unlike PTFs' empirical equations, the ML algorithms can capture non-linear and complex relationship (Wang *et al.*, 2024; Kawamura *et al.*, 2021). Additionally, ML models can process multiple soil properties at the same time. While PTFs perform well in a smaller-scale, machine learning approaches are effective in large-scale studies (Zhou *et al.*, 2019). Some of the most popular ML techniques to predict D_b are k-NN, neural networks, random forest, support vector machines, cubist regression models, etc. (Panagos *et al.*, 2024; Padarian *et al.*, 2020). All these techniques can consider multiple soil variables to predict bulk density which might produce even better results compared to the empirical equations. Padarian *et al.*, (2020) found that neural networks, support vector machine, and random forest are the best ML approaches because of their capability to handle intricate relationship compared to the simpler techniques, such as regression models.

Machine learning algorithms have been successfully used to model soil bulk density based on multispectral remote-sensing data. For example, Landsat-7's spectral bands were utilized, with extreme gradient boosting achieving the highest classification accuracy (88%) for salt marsh soils. Both random forest and gradient boosting were effective in identifying key predictors, such as specific spectral bands, for bulk density classification (Hikouei et al., 2021). SVM has also been applied alongside random forest and gradient boosting.

While SVM tends to be slightly less accurate than ensemble methods like other two techniques, it remains a robust choice for smaller dataset (Grunwald et al., 2024; Hikouei et al., 2021). Finally, an uncertainty test is important for the developed models used to predict soil properties. A widely accepted uncertainty assessment technique is the application of bootstrapping while training a model (Stine, 1985).

Conclusion

The study highlights the effectiveness of both pedotransfer functions and machine learning algorithms in predicting soil bulk density. PTFs have been widely used for their simplicity and reliability on readily available soil data but are often constrained by their regional specificity and limited accuracy in diverse conditions. Machine learning, on the other hand, provides better predictive performance by accounting for complex and nonlinear relationships among soil properties. Advanced ML models such as random forests and artificial neural networks outperform traditional PTFs, particularly in large-scale studies. However, the integration of these techniques with robust validation methods, such as k-fold cross-validation and uncertainty analysis, is essential for ensuring reliable predictions. Overall, combining PTF and ML approaches can offer a more comprehensive and scalable solution for D_b modeling.

Most of the developed PTFs have considered soil organic matter as a single input to predict D_b which can be responsible for overestimation when there is high amount of SOM. Additionally, PTFs are often tailored to specific soil types, climates, and land uses, limiting their transferability to other regions. Regarding the machine learning models, they require extensive datasets with diverse soil properties, which may not always be available. Also, ML algorithms, especially complex models like neural networks, can suffer from overfitting if not properly tuned and validated.

References

Abdelbaki, A.M., 2016. Evaluation of pedotransfer functions for predicting soil bulk density for U.S. soils. *Ain Shams Eng. J.,* 9(4): 1611-1619. https://doi.org/10.1016/j.asej.2016.12.002

Alexander, E.B., 1980. Bulk densities of California soils in relation to other soil properties. *Soil Sci. Soc. Am. J.,* 44: 689–92. https://doi.org/10.2136/sssaj1980.03615995004400040005x

Benites, V.M., Machado, P.L.O.A., Fidalgo, E.C.C., Coelho, M.R., Madari, B.E., 2007. Pedotransfer functions for estimating soil bulk densityfrom existing soil survey reports in Brazil. *Geoderma,* 139: 90–97. https://doi.org/10.1016/j.geoderma.2007.01.005

Chen, S., Richer-de-Forges, A.C., Saby, N.P.A., Martin, M.P., Walter, C., Arrouays, D., 2018. Building a pedotransfer function for soil bulk density on regional dataset and testing its validity over a larger area. *Geoderma,* 312: 52-63. https://doi.org/10.1016/j.geoderma.2017.10.009

Grunwald, S., Murad, M.O.F., Farrington, S., Wallace, W., Rooney, D., 2024. Multi-Sensor Soil Probe and Machine Learning Modeling for Predicting Soil Properties. *Sensors,* 24(21): 6855. https://doi.org/10.3390/s24216855

Håkansson, I., Lipiec, J., 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. *Soil Tillage Res.,* 53(2): 71-85. https://doi.org/10.1016/S0167-1987(99)00095-1

Han, G.Z., Zhang, G.L., Gong, Z.T., Wang, G.F., 2012. Pedotransfer functions for estimating soil bulk density in China. *Soil Sci.,* 177(3): 158-164. http://dx.doi.org/10.1097/SS.0b013e31823fd493

Han, Y., Zhang, J., Mattson, K.G., Zhang, W., Weber, T.A., 2016. Sample sizes to control error estimates in determining soil bulk density in California forest soils. *Soil Sci. Soc. Am. J.,* 80: 756-764. https://doi.org/10.2136/sssaj2015.12.0422

Hikouei, I.S., Kim, S.S., Mishra, D.R., 2021. Machine-Learning Classification of Soil Bulk Density in Salt Marsh Environments. *Sensors,* 21(13): 4408. https://doi.org/10.3390/s21134408

Hollis, J.M., Hannam, J., Bellamy, P.H., 2011. Empirically-derived Pedotransfer functions for predicting bulk density in European soils. *Eur. J. Soil Sci.,* 63: 96–109. https://doi.org/10.1111/j.1365-2389.2011.01412.x

Kawamura, K., Nishigaki, T., Andriamananjara, A., Rakotonindrina, H., 2021. Using a One-Dimensional Convolutional Neural Network on Visible and Near-Infrared Spectroscopy to Improve Soil Phosphorus Prediction in Madagascar. *Remote Sens.,* 13(8): 1519. https://doi.org/10.3390/rs13081519

Manrique, L., Jones, C., 1991. Bulk density of soils in relation to soil physical and chemical properties. *Soil Sci. Soc. Am. J.,* 55: 476–81. https://doi.org/10.2136/sssaj1991.03615995005500020030x

Nanko, K., Ugawa, S., Hashimoto, S., Imaya, a., Kobayashi, M., 2014. A pedotransfer function for estimating bulk density of forest soil in Japan affected by volcanic ash. *Geoderma,* 213: 36-45. https://doi.org/10.1016/j.geoderma.2013.07.025

Padarian, J., Minasny, B., and McBratney, A.B., 2020. Machine learning and soil sciences: a review aided by machine learning tools. *Soil,* 6: 35–52, https://doi.org/10.5194/soil-6-35-2020

Palladino, M., Romano, N., Pasolli, E., Nasta, P., 2022. Developing pedotransfer functions for predicting soil bulk density in Campania. *Geoderma,* 412: 115726. https://doi.org/10.1016/j.geoderma.2022.115726

Panagos, P., De Rosa, D., Liakos, L., Labouyrie, M., Borrelli, P., Ballabio, C., 2024. Soil bulk density assessment in Europe. *Agric. Ecosyst. Environ.,* 364: 108907. https://doi.org/10.1016/j.agee.2024.108907

Prévost, M., 2004. Predicting soil properties from organic matter content following mechanical site preparation of forest soils. *Soil Sci. Soc. Am. J.,* 68: 943–949. https://doi.org/10.2136/sssaj2004.9430

Reis, A.M.H.D., Teixeira, W.G., Fontana, A., Barros, A.H.C., Victoria, D.D.C., Vasques, G.M., 2024. Hierarchical pedotransfer functions for predicting bulk density in Brazilian soils. *Sci. Agric.,* 81: e20220255. https://doi.org/10.1590/1678-992X-2022-0255

Ruehlmann, J., Körschens, M., 2009. Calculating the effect of soil organic matter concentration on soil bulk density *Soil Sci. Soc. Am. J.,* 73(3): 876–885. https://doi.org/10.2136/sssaj2007.0149

Sequeira, C.H., Wills, S.A., Seybold, C.A., West, L.T., 2014. Predicting soil bulk density for incomplete databases. *Geoderma,* 213: 64-73. https://doi.org/10.1016/j.geoderma.2013.07.013

Stine, R.A., 1985. Bootstrap prediction intervals for regression, *J. Am. Stat. Assoc.,* 80: 1026–1031.

Wang, X., Sun, H., Wang, C., Liu, J., Guo, Z., Gao, L., 2024. Predicting the soil bulk density using a new spectral PTF based on intact samples. *Geoderma,* 449: 117005. https://doi.org/10.1016/j.geoderma.2024.117005

Yi, X., Li, G., Yin, Y., 2016. Pedotransfer Functions for Estimating Soil Bulk Density: A Case Study in the Three-River Headwater Region of Qinghai Province, China. *Pedosphere,* 26(3): 362-373. https://doi.org/10.1016/S1002-0160(15)60049-2

Zhou, J., Li, E., Wei, H., Li, C., Qiao, Q., Armaghani, D.J., 2019. Random forests and cubist algorithms for predicting shear strengths of rockfill materials. Appl. Sci., 9(8): 1621. https://doi.org/10.3390/app9081621

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

The evaluation of soil quality in Sivas Ulaş using integrated quality index model and prediction with artificial neural network

Elis-bright Iteke MOLUA *, Orhan DENGİZ, Sena PACCİ
Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Elis-bright Iteke MOLUA
brightmolua2@gmail.com

Abstract

The present study aims to calculate and assess the soil quality of pasture area soils based on Integrated Quality Index and predict using Artificial Neural Network. For this aim, in Acıyurt pasturelands of Ulaş District, Sivas Province, soil samples were collected to evaluates the physical, chemical, and biological characteristics of the soil. 10 soil characteristic properties were considered, including 3 physical, 5 chemical, and 2 biological properties. The IQI (Integrated Quality Index) and ANN (Artificial Neural Network) models were used to calculate and assess the soil quality of that area and from the results it was classified as "medium quality". Structural stability had the highest score and had a positive effect on the general quality of the pasture soil. The soil quality values were estimated by ANN with a high accuracy of 94%. In addition, soil quality index obtained by scoring functions were found to be statistically similar when compared with the values estimated by ANN. The spatial distribution map was produced using the Simple Gaussian method under the Kriging method. Based on the overall soil quality distribution map, it was determined that the quality of the soils located in the western part of the study area was higher than those in the eastern part.

Keywords: Soil quality, Geographic information system (GIS), Integrated Quality Index (IQI), Artificial Neural Network (ANN), Soil assessment

Introduction

Soil and land degradation have been a growing concern over the years due to rapid deforestation, industrialization and rapid urbanization. Soil is an element of the land. Land includes soil, climate, geology, relief, hydrology, and land cover (FAO 1976; Sarıoğlu, et al. 2012). Soil refers to natural material on the Earth's surface composed of unconsolidated organic and inorganic solids, liquid, and gases. Soil is a natural body which sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Mausbach and Tugel, 1995, modified).

Soil quality is defined as the capacity to maintain biological productivity and environmental quality within the land use and ecosystem for soils, as well as to improve plant, animal and human health (Doran and Parkin, 1994). The soil properties which are physical, chemical and biological make up the soil quality. If soil quality decreases, it will have an effect on the productivity of the soil and crop yield. Therefore, it is important to monitor and assess soil quality frequently. Soil quality can be improved by increasing soil cover, improving root development, combining plant and animal production, increase biodiversity, and reduce soil manipulation (USDA 2022). Soil quality is crucial to ecosystem health.

Integrated Quality index (IQI) is used to evaluate soil quality. It was created to generate multiple soil indicators into a single, comprehensive metric. IQI is very good in predicting soil quality, it provides an assessment of soil health by integrating soil physical, chemical and biological properties (Karlen et al, 2003).

An artificial neural network (ANN) is a computational model that is inspired by the way the human brain works. It is made up of layers of interconnected 'neurons', which process and transmit information (Dede et al., 2022). In addition, Geographic Information Systems (GIS) are important tools for assessing soil quality and mapping its spatial distribution. GIS technology has enabled the spatial variability computation of different phenomena (Burrough et al., 2015). GIS is used to map and analyze the spatial distribution of soil quality indicators. This study aims to calculate and assess the soil quality of pasture area soils based on Integrated Quality Index and predict using Artificial Neural Network

Material and Methods

General features of the study area

The study area is located within the borders of Ulaş and Altınyayla districts of Sivas province. Most of the area is the pasture of Acıyurt village in Ulaş district and is located between the coordinates of 323000-336000 W-E and 4348000-4353800 G-K (WGS84, Zone 37, UTM m) (Figure1).

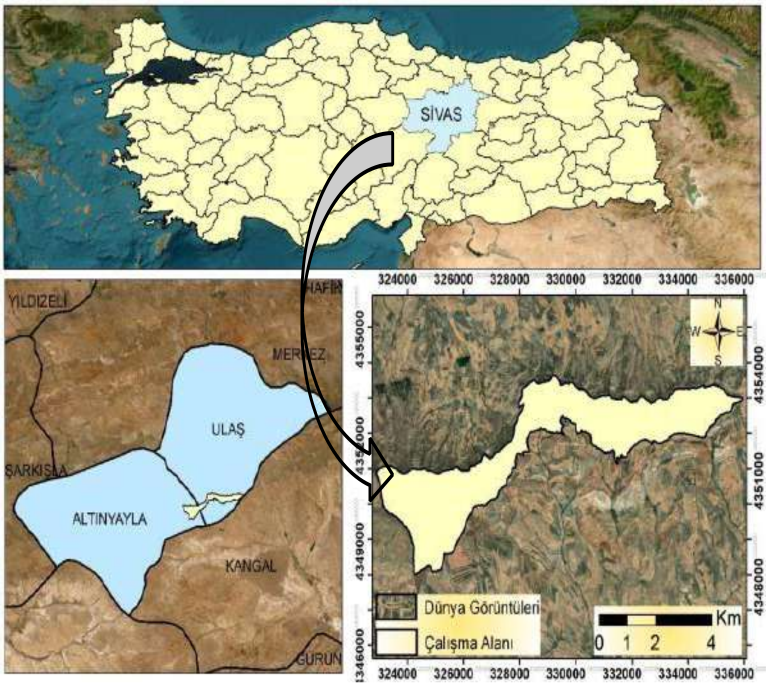


Figure 1: Location map of the study area

Figure 2: Location map of the Study Area

Sivas Province, which is in the Central Anatolia Region for the most part, also has lands in the Black Sea Region and the Eastern Anatolia Region. Most of its lands are in the Kızılırmak and some in the Fırat and Yeşilırmak basins. In terms of surface area, it is the 2nd largest province in Turkey after Konya. In Sivas, which has an average altitude of over 1000 meters above sea level, mountains, valleys extending between mountains, plains in the hollow areas and plateaus in the high parts constitute the landforms of the city. The study area is approximately 1849.21 ha, and its altitude above sea level varies between 1635 m and 1938m (Figure 2).

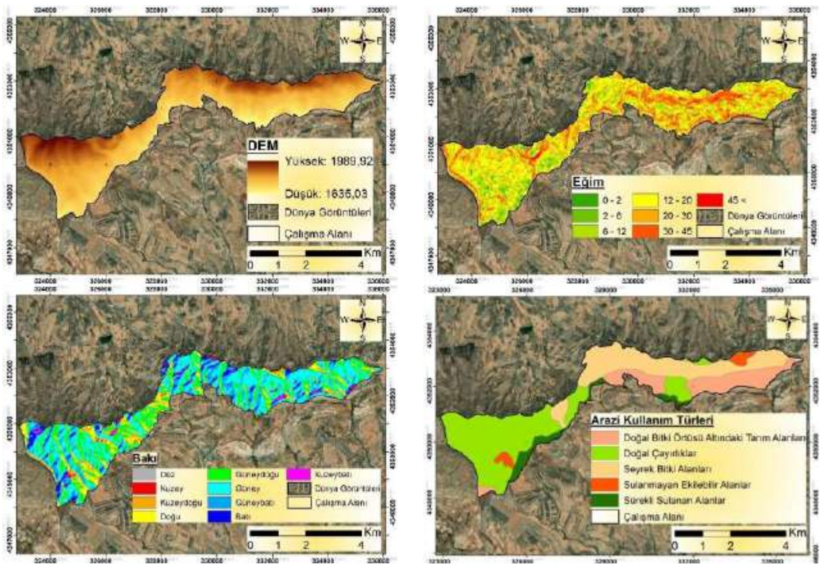


Figure 2. Digital elevation model, elevation, aspect and slope maps of the study area.

In Sivas province, which has a harsh continental climate structure, winters are cold and harsh, as well as having plenty of snowfall. Summer months are hot and dry for short periods. In addition, rain is effective in spring and autumn months. When long-term climate data are examined, the coldest month is January with -34.6ºC. The hottest month is July with 38.3ºC. The highest monthly precipitation average is May, and the lowest is August. In addition, the annual average precipitation varies between 460-470 mm, while the annual average temperature varies between 8-12ºC (Anonymous, 2024). In the map obtained by using the data of Corine (2018) to determine the land cover/land use type, the highest spread within the area is the usage type that shows the area is composed of natural meadows and sparsely planted areas. The digital elevation model of the area, maps of slope, aspect and land use types are shown in Figure 2, respectively.

Collection of soil samples and analysis

The area was divided into grids of 200m x 200m, and using the global positioning system (GPS), the locations of soil samples were identified. Soil sampling was collected on a total of 152 at 0–20 cm depth from cultivation areas. The samples collected are placed in a plastic bag and transported to the laboratory. The soil samples are allowed to air, crushed and sieved through a 2mm sieve to prepare them for analysis. For the biological analysis, soils are kept in the ice bags and directly put into the freezer at +4 degrees after being taken from the field. Laboratory analysis was carried out to test the soil physical, chemical and biological parameters to determine the soil quality status of the study area.

The soil quality index within the study area was determined through the application of Principal Component Analysis (PCA) to 31 indicators. PCA is a statistical method used to reduce a case-variable data table to its fundamental features. PCA aids in the assessment of soil quality and the creation of a minimum data set (MDS) which provides a comprehensive overview of the study area. In the research, factor analysis will be conducted to examine the relationships between the 31 soil properties. The purpose of the Principal Component Analysis is to establish the factors that will facilitate the creation of the minimum data set.

To get the weighting value the effective indicators in both the TDS and MDS, the communalities of each indicator were calculated through factor analysis using SPSS software (Cherubin et al., 2016). Descriptive statistics were used to describe and summarize the features of the datsets. For this purpose, the ratio of the communality value of each property to the sum of the communality values of all indicators in each set (TDS and MDS) (Equation 1) was considered as the weight of each indicator (Biswas et al., 2017). Finally, by combining the scores and weights of different indicators, the Integrated Quality Index (IQI) was calculated using Equations (2):

$$Weighting\ factor = (Communality)/(Sumofcommunalities) \tag{3}$$

$$IQI = \sum_{i=1}^{n} NiWi \tag{4}$$

Soil properties have different scales and units; therefore, it is necessary to convert soil factors into unitless scores ranging from zero to one. To achieve this, data ranking or standardization was employed using standard scoring functions (SSF), assigning scores ranging from 0 to 1 (Andrews et al., 2002a; Andrews et al., 2002b). According to this method, different soil properties follow three functions (Karlen et al., 2014):

1. The "Optimum Range" function (OR), where scores are distributed using either of the previous functions based on whether the value of this index is more or less than the optimum range (e.g., soil reaction: pH).00

2. The "More is Better" function (MB), used for soil indicators that improve soil quality (e.g., organic matter: OM).

3. The "Less is Better" function (LB), used for soil indicators that reduce soil quality (e.g. Hydraulic conductivity: HC).

The equations used for scoring soil properties between 0.1 and 1.0, "less is better" (Equation 5) and "more is better" (Equation 6), are as follows:

$$f\ (x) = \begin{cases} 0.1 & x \geq L \\ 1 - 0.9 \times \frac{x-L}{U-L} + 1 & L \leq x \leq U \\ 1.0 & x \leq U \end{cases} \tag{5}$$

$$f\ (x) = \begin{cases} 0.1 & x \geq L \\ 0.9 \times \frac{x-L}{U-L} + 0.1 & L \leq x \leq U \\ 1.0 & x \leq U \end{cases} \tag{6}$$

The Soil Quality Index parameters will be used to generate the soil quality distribution maps of the study area. ANN models are designed based on the working principle of biological neural networks. Artificial neural networks have a feature that provides more convenience than statistical techniques in terms of predictions, especially in nonlinear systems. With this feature, ANN has become the most important method in solving complex nonlinear problems (Odabas et al. 2014a, b, 2016). Levenberg–Marquardt (LM) algorithm was performed to train the network in this research. ANN was implemented in MATLAB software Matlab® R2012a (7.14.0.739) 32-bit (win32).

The ANN is a model that has been assimilated to improve the method for predicting soil quality index (SQIANN). The model occurs of multiple layers of nodes with input layers, hidden layers, and output layer. The weights and biases can be adjusted during the training process to improve the accuracy of the ANN's predictions.

To prepare the distribution map, The RMSE (root mean square error) model was used and the smallest RMSE was selected. 15 different geostatistical analyzed methods were used to prepare soil quality distribution map. In the results the least RMSE is the simple gaussian method from kriging method.

Results And Discussion

Descriptive Statistics

As demonstrated in Table 1 the pH values of the soils range from 6.93 to 8.34, with an average of 7.80, placing them in the lightly alkaline reaction class. Based on the content of sand, silt, and clay in the soil samples from the study area, six texture classes were determined: clay, clay loam, loam, sandy clay loam, sandy clay, and sandy loam. The organic matter content of the soils varied from a minimum of 0.36% to a maximum of 17.22%, with an average of 7.76%, placing it in the high class (>4%) according to Olsen and Dean (1965). Organic matter, which has a significant impact on soil fertility parameters, plays a crucial role in the formation and stability of soil aggregates (Saygın et al., 2019). The aggregate stability of the soils in the study area was found to vary between 9.51% and 87.25%, with an average of 58.26%, depending on organic matter and its content. In a study by Wagner et al. (2000), a positive relationship between aggregate stability and clay content was found. According to this study, as clay content increases, the specific surface area of the soil also increases, thereby enhancing aggregate stability. The MBC content of the soils in the study area ranged from a minimum of 5.88 to a maximum of 72.99, with an average of 38.19. Previous studies have shown that variations in microbial populations and activities serve as a good indicator of changes in soil health and quality (Kennedy and Papendick, 1995; Pankhurst et al., 1995).

Table 1: Descriptive Statistics for Soil Samples from the Study Area

Soil properties	AV	St,D	CV	Variance	Min V	Max V	Skewness	Kurtosis
%Sand	41.80	9.87	23.61	97.54	14.74	81.86	0.10	1.41
%Silt	23.90	5.84	24.43	34.22	3.64	43.29	-0.18	1.64
%Clay	34.28	9.29	27.10	86.42	10.48	67.83	0.47	0.80
%OM	7.76	3.63	46.77	13.17	0.36	17.22	0.32	-0.32
HA	1.26	0.09	7.142	0.00	1.06	1.56	0.26	0.16
%AS	58.26	19.35	33.21	374.46	9.51	87.25	-0.53	-0.83
pH	7.80	0.28	3.58	0.08	6.93	8.34	-0.85	0.75
EC (ds/m)	0.54	0.16	29.62	0.02	0.13	1.00	0.004	-0.22
MBC	38.19	12.95	33.90	167.80	5.88	72.99	-0.19	-0.62
K mek/100g	0.66	0.45	68.18	0.21	0.09	1.89	0.87	-0.33
P mg/kg	3.55	3.91	110.14	15.36	0.01	24.28	2.60	8.74

AV: Average, St.D: Standard Deviation, CV: Coefficient of variation, Min V: Minimum value, Max V: Maximum value, OM: Organic matter, HA: Bulk Density, AS: Aggregate Stability, MBC: Microbial Biomass Carbon.

Wilding (1985) classified the coefficient of variation (CV) as low (<15%), medium (15-35%), and high (>35%). Based on this classification, the soil properties of the study area showed the following variation: soil bulk density and pH exhibited "low" variation with less than 15% variability, while sand, silt, clay, AS (aggregate stability), EC (electrical conductivity), MBC exhibited "medium" variation with 15-35% variability. Organic matter (OM), potassium (K), and phosphorus (P) showed "high" variation with more than 35% variability.

Silt, AS, pH, and MBC values were negatively skewed, while other properties exhibited positive skewness. In a right-skewed distribution, the values are concentrated below the mean, while in a left-skewed distribution, they are concentrated above the mean. The property with the highest skewness, showing the greatest deviation from a normal distribution, was phosphorus (P). The right-skewed, left-biased distribution of P indicates that a large portion of the phosphorus content in the soils is below the average level (3.55 mg/kg).

Among the soil properties, OM, AS, EC, MBC, and K showed a flatter distribution compared to normal distribution, while other parameters exhibited a steeper distribution.

Principal component Analysis (PCA)

To create a minimum data set PCA was applied. The eigenvalues and the number of principal components explaining the variance are presented in Table 1. In determining the parameters that can be included in the minimum data set, the component loadings determined by PCA, the sums of correlation loadings, and correlation analysis methods between the data were considered. The results of the PCA indicated that seventh principal components with eigenvalues greater than one collectively explained 75.119% of the variance (Table 2). The PCA analysis resulted in the creation of a minimum data set comprising 10 of the 31 indicators considered in the total data set. The first principal component accounted for 30.629% of the variance. The remaining components explained variances of 15.820%, 8.220%, 7.409 %, 5.424%, 4.096%, and 3.520%, respectively.

Table 2. The eigenvalues and the number of principal components

Components	Total	Eigenvalues Variance %	Cumulative Variance %
PCA-1	9.189	30.629	30.629
PCA-2	4.746	15.820	46.449
PCA-3	2.466	8.220	54.669
PCA-4	2.223	7.409	62.078
PCA-5	1.627	5.424	67.502
PCA-6	1.229	4.096	71.599
PCA-7	1.056	3.520	75.119

In selecting features for the principal components, the feature with the highest loading was chosen, and features with weights within 10% of that loading were considered (Table 3). Other features were subsequently excluded from the data set. Furthermore, among the features exhibiting high correlation within the data set, selections were made to ensure minimal redundancy (Alaboz, 2020).

Table 3. Principal components and the weights of the features in each principal component

Parameters	Component							Total correlation loads
	PCA-1	PCA-2	PCA-3	PCA-4	PCA-5	PCA-6	PCA-7	
%Sand	0.160	0.711	0.600	0.137	0.128	0.114	0.063	6.762
%Silt	0.056	0.155	0.703	0.293	0.340	0.223	0.082	4.844
%Clay	0.134	0.853	0.195	0.038	0.077	0.020	0.119	7.413
AW	0.251	0.390	0.575	0.392	0.117	0.028	0.080	6.208
HC	0.180	0.847	0.025	0.011	0.048	0.148	0.019	7.574
BD	0.602	0.437	0.499	0.163	0.212	0.032	0.102	9.835
%AS	0.739	0.271	0.080	0.198	0.048	0.270	0.001	10.981
SSI	0.100	0.829	0.456	0.208	0.010	0.020	0.051	7.504
DO	0.441	0.607	0.027	0.208	0.182	0.243	0.004	8.731
CF	0.766	0.508	0.029	0.066	0.070	0.059	0.124	12.060
%OM	0.851	0.335	0.124	0.015	0.048	0.021	0.151	12.562
%OC	0.851	0.335	0.124	0.015	0.048	0.021	0.151	12.562
%CaCO3	0.504	0.282	0.174	0.100	0.214	0.064	0.014	8.165
pH	0.761	0.245	0.275	0.207	0.155	0.133	0.145	11.148
EC (ds/m+1)	0.625	0.246	0.059	0.124	0.253	0.180	0.379	9.608
mgCO2/gFKT/24h	0.562	0.206	0.371	0.273	0.165	0.447	0.076	9.012
mgMBC/gFKT/24h	0.877	0.126	0.080	0.005	0.084	0.064	0.155	12.688
qCO2	0.373	0.234	0.505	0.194	0.266	0.512	0.081	6.761
µg p+nitrofenol/gFKT/h	0.882	0.087	0.102	0.037	0.108	0.064	0.047	12.710
Ca mek/100g	0.682	0.197	0.050	0.019	0.112	0.333	0.240	10.007
Mg mek/100g	0.178	0.099	0.056	0.189	0.284	0.257	0.711	3.851
K mek/100g	0.783	0.131	0.071	0.063	0.115	0.175	0.052	11.115
Na mek/100g	0.524	0.168	0.013	0.063	0.234	0.039	0.066	8.039
Fe ppm	0.468	0.108	0.127	0.033	0.469	0.284	0.294	7.288
Cu ppm	0.382	0.310	0.062	0.125	0.386	0.190	0.076	6.744
Mn ppm	0.390	0.073	0.357	0.392	0.284	0.189	0.271	6.632
Zn ppm	0.100	0.434	0.035	0.016	0.523	0.144	0.006	4.961
P ppm	0.295	0.210	0.168	0.838	0.226	0.157	0.006	6.228
%N	0.767	0.110	0.104	0.073	0.382	0.221	0.103	11.044

AW: Available water, HC: Hydraulic conductivity, BD: Bulk density, AS: Aggregate stability, SSI: Structural stability index, DO: Dispersion ratio, CF: Crust formation, OM: Organic matter, OC: Organic carbon, EC: Electrical conductivity, MBC: Microbial biomass carbon.

In PCA-1, the features with the highest weights were identified as p+nitrophenol, MBC, OM. and OC. A high correlation (>0.6) was found among these parameters, and the feature with the highest total correlation loading, p+nitrophenol and organic matter was selected and included in the PCA-1 dataset. The high correlation between soil properties indicates that the contribution ratios of the selected features are similar. In PCA-2, the feature with the highest weight was Clay, HC and SSI. HC and SSI were selected for PCA-2. In PCA-3, the feature with the highest weight was Silt; in PCA-4, the feature with the highest weight were P ppm and P_2O_5 ppm. P ppm was selected for PCA-4; in PCA-5, the feature with the highest weight were Zn ppm and Fe ppm. Both were selected for PCA-5; in PCA-6 the feature with the highest weight was qCO_2; in PCA-7 the feature with the highest weight was Mg mek. These features were included in the minimum dataset.

Standard Scoring Function (SSF)

The scoring function was assigned after the creation of the MDS and the calculation of MB and LB. SQI was calculated with the weighted value gotten after running SPSS.

- The "More is Better" function (MB), used for soil indicators that improve soil quality (e.g., organic matter: OM).
- The "Less is Better" function (LB), used for soil indicators that reduce soil quality (e.g. hydraulic conductivity).

Artificial Neural Network (ANN)

In this research, Silt, hydraulic conductivity, structural stability, CO_2, Organic matter content and Phosphorus were used as input data. Soil quality index (SQI) was output data. Total samples were 152 and 106 of the total samples were used as training data (70%). 23 samples (15%) were used as testing and 23 samples (15%) as validation data (Figure 3**).** After the process of training was finished and all weighing indications were adjusted, the ANN fully approximate the output data as a function of input values. The optimum model gained in this study occurred of 6 input, 10 hidden layer and 1 output layer (Figure 3).

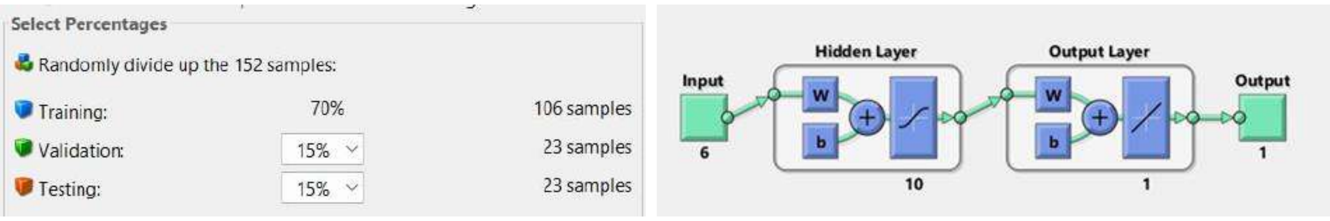
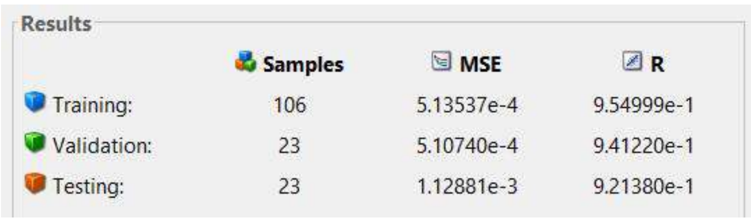


Figure 3. Artificial neural network model separating data into 3 parts and Single hidden layer network model

In the results of the study, soil quality index (SQI) values were evaluated using ANN. The MSE and R values obtained are shown in figure 4. Upon examination, it was found that the MSE was low and the R value was quite high. This indicates that the ANN structure produces high accuracy predictions. The values were evaluated as training, validation, and testing.



Results

	Samples	MSE	R
Training:	106	5.13537e-4	9.54999e-1
Validation:	23	5.10740e-4	9.41220e-1
Testing:	23	1.12881e-3	9.21380e-1

Fig. 4. Result of artificial neural network model

The histogram indicates the error for the 12 bins for the validation, the testing of the performance, and training data of the normalized data (Figure 5). For the hidden layer, the best fit was registered at epoch 12. Most of the predicted value was near to the real data because of the error value that was close to zero error. For the chosen epoch, performance describes the best-fit value. Performance curve at 6 epoch and the best validation is 0.00051074.

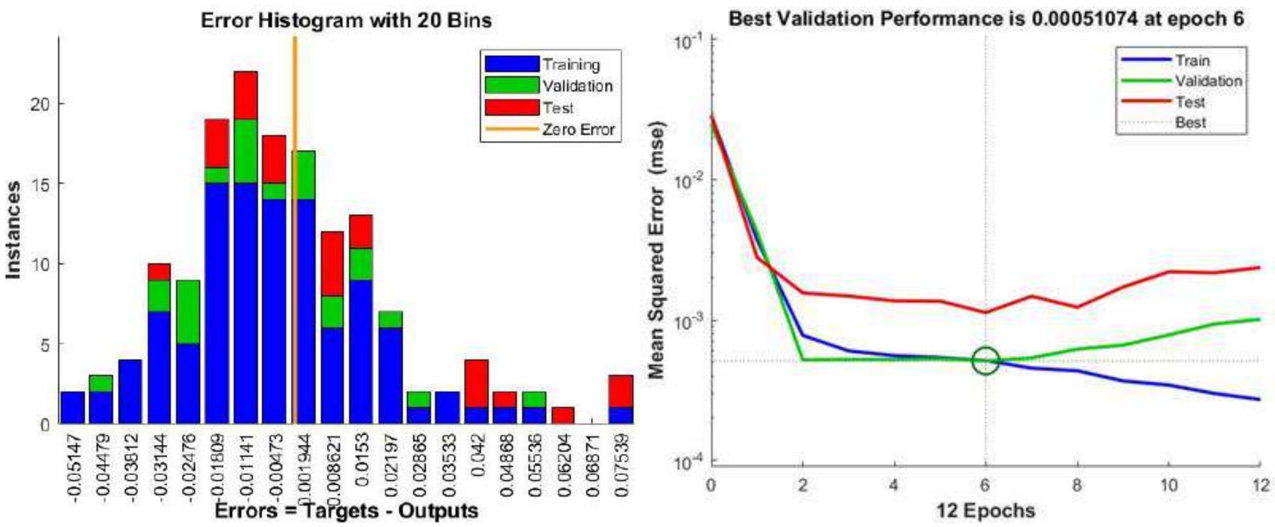


Figure 5. The error histogram for the training of the data using the Levenberg–Marquardt using the back-propagation and results for the validation performance curve

The MSE of the testing performance and training exceeded the validation performance. For fitting the results, LM was implemented in the hidden layer where the backward propagation of errors was applied. ANN calculated soil quality with 94% in figure 6. The correlation demonstrates between the actual values estimated and plotted on the x-axis values recorded on the y-axis for all data, testing data, training data, and validation data. As a useful indicator, the coefficient of determination (R2) is for discovering the performance of forecast the proposed artificial neural network. Thus, the accuracy of soil quality was estimated using physical, chemical and biological soil parameters.

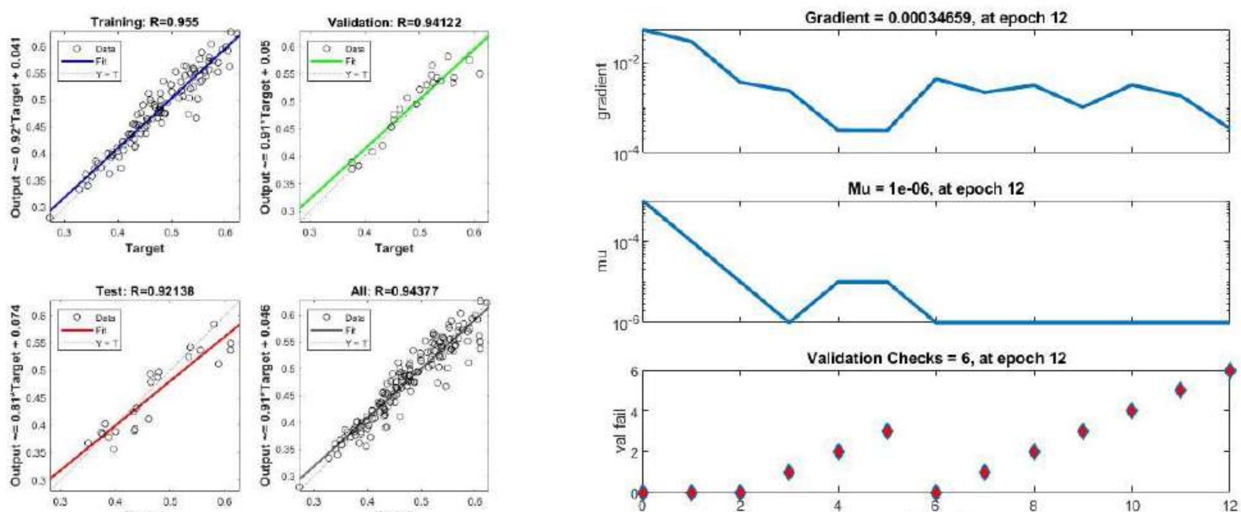


Fig. 6. The results for the regression between the output data and the targets for the LM approach and the plot for the training state parameters for the 12 epochs

In the IQI map (figure 7), soil quality is classified as follows: Low, Medium and High. On the Western side of the map the soil quality is medium, going towards the Eastern part it gets low quality. The reason is because structural stability has a positive effect on the soil which increases the soil quality. Structural stability is affecting the soil more than the other parameters because it has the highest correlation between all the parameters and affects them positively. Structural stability is affected by clay and organic matter, when organic matter increases structural stability increases. Based on the overall status of the map the soil quality in this area is medium quality. According to statistical analysis, there were no statistically significant differences between the soil quality index values obtained from IQI and that of ANN. After reviewing the maps, it was observed that the two different soil quality methods applied to the same study area revealed the quality status of the area with high similarity.

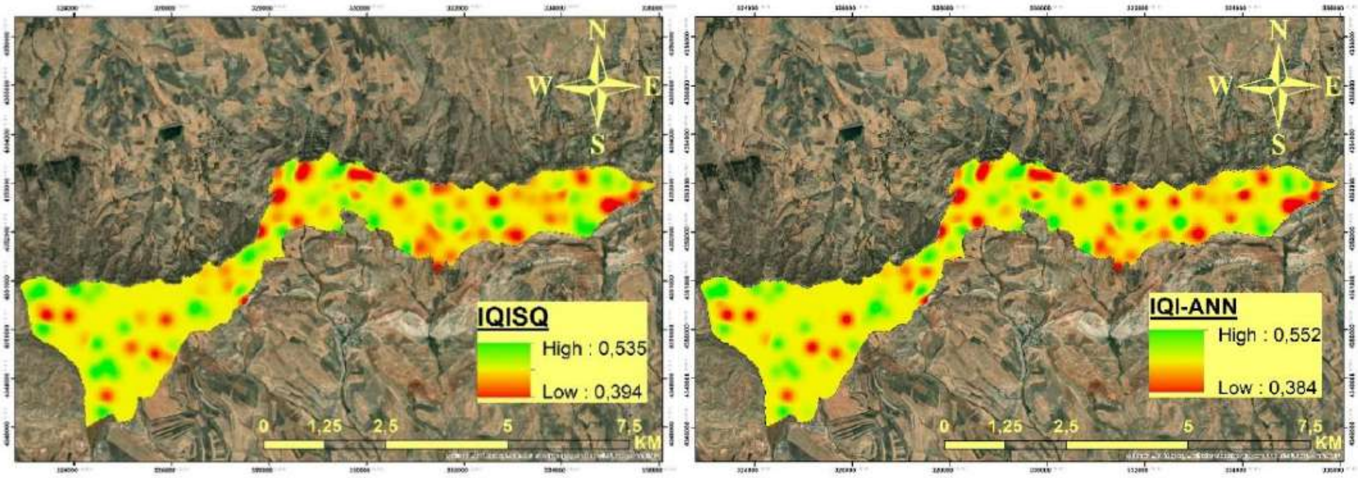


Fig. 7. Integrated Quality Index Soil Quality map and Soil quality predicted by ANN.

Conclusion

The aim of this study was to evaluate the soil quality of the soil in Acıyurt village of Ulaş district, Sivas province. The IQI model was used to integrate the soil physical, chemical and biological functions to accurately assess soil quality and evaluate its predictability using artificial neural networks (ANN). The results obtained showed that the physical quality score was medium, the chemical quality score was high, the biological quality score was low, and the overall quality score was medium. Soil quality index obtained by scoring functions were found to be statistically similar when compared with the values estimated by ANN. In addition, with large datasets, it has been determined that ANN can determine soil quality with a very good performance. To improve the soil quality of the soil in the area measures such as monitoring and evaluation of quality changes over the years. Also crop rotation and intercropping can also help improve soil quality. This study demonstrates that the ANN model can be a significant tool for evaluating soil quality and providing decisions regarding sustainable land use and management practices.

References

Alaboz, P., 2020. Selecting soil properties for assessment of soil aggregation using principal component and clustering analyses. *Soil Research*, *59*(2), 170-178.

Andrews, S.S., Karlen, D.L., Mitchell, J.P., 2002. A comparison of soil quality indexing methods for vegetable production systems in Northern California. *Agriculture, ecosystems & environment*, *90*(1), 25-45.

Biswas, S., Hazra, G.C., Purakayastha, T.J., Saha, N., Mitran, T., Roy, S.S., Mandal, B., 2017. Establishment of critical limits of indicators and indices of soil quality in rice-rice cropping systems under different soil orders. *Geoderma*, *292*, 34-48.

Burrough, P.A., McDonnell, R., McDonnell, R.A., Lloyd, C.D., 2015. Principles of Geographical Information Systems, 3rd ed.; Oxford University Press: Oxford, UK, 2015.

Cherubin, M. R., Karlen, D. L., Franco, A. L., Tormena, C. A., Cerri, C. E., Davies, C. A., Cerri, C.C., 2016. Soil physical quality response to sugarcane expansion in Brazil. *Geoderma*, *267*, 156-168.

Dede, V., Dengiz, O., Turan, I.D., Zorlu, K., Pacci, S., Serin, S., 2022. Determination of erosion sensitivity of soils formed on the periglacial landforms of Ilgar Mountain and their prediction using artificial neural networks (ANN). Int. J. Geogr. Geogr. Educ. (47), 258–279.

Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. SSSA, Madison, WI, pp. 3-21.

FAO, 1976. A framework for land evaluation: Soils Bulletin 32, Food and Agriculture Organization of the United Nations, Rome, İtaly.

Karlen, D.L., Ditzler, C.A., 2003. Soil quality: Why and How? Geoderma. 114(3-4), 145-156.

Karlen, D.L., Stott, D.E., Cambardella, C.A., Kremer, R.J., King, K.W., McCarty, G.W., 2014. Surface soil quality in five midwestern cropland Conservation Effects Assessment Project watersheds. J. Soil Water Conserv. 69 (5), 393–401.

Mausbach M.J., Tugel AJ., 1995. Soil quality and the natural resources conservation. Agronomy Abst 1995;337.

Odabas, M.S., Leelaruban, N., Simsek, H., Padmanabhan, G., 2014. Quantifying impact of droughts on barley yield in north dakota, usa using multiple linear regression and artificial neural network. Neural Network World 24(4):343–355

Odabas, M.S., Temizel, K.E., Caliskan, O., Senyer, N., Kayhan, G., Ergun, E., 2014b. Determination of reflectance values of hypericum's leaves under stress conditions using adaptive network based fuzzy inference system. Neural Network World 24(1):79–87

Odabas, M.S., Kayhan, G., Ergun, E., Senyer, N., 2016. Using artificial neural network and multiple linear regression for predicting the chlorophyll concentration index of Saint John's Wort Leaves. Commun Soil Sci Plant Anal 47(2):237–245

Olsen, S.R., Dean, L.R., 1965 Phosphorus. In: Methods of Soil Analysis, American Society of Agronomy, Madison, Wisconsin, No. 9, 920-926.

Kennedy, A.C., Papendick, R.I., 1995. Microbial characteristics of soil quality. Journal of soil and water conservation, 50(3), 243-248.

Sarıoğlu, F.E., Dengiz, O., 2012. Parametric approach with linear combination technique in land evaluation studies. Journal of Soil and Water 1(2):82–87

Saygın, F., Dengiz, O., İç, S., İmamoğlu, A., 2019. Evaluation of the relationships between some physico-chemical soil properties and some erodibility parameters at the micro-basin scale. Artvin Coruh University, Journal of the Faculty of Forestry, 20 (1): 82-91.

USDA, 2022. Soil health. United States department of agriculture. Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/main/nd/soils/health/.

Wagner, S., Cattle, S.R., Scholten, T., Felix-Henningsen, P., 2000. Observing the Evolution of Soil Aggregates From Mixtures of Sand, Clay and Organic Matter In Soil. New Zealand Society of Soil Science. 3: 217-218.

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

GIS-based spatial assessment of soil organic carbon and its influence on physical soil quality indicators in micro watershed level

Endalamaw Dessie ALEBACHEW [1,2,*], Orhan DENGIZ [2]

[1] Hawassa University, Department of Soil Resource and Watershed Management, Wondo Genet, Ethiopia
[2] Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Endalamaw Dessie ALEBACHEW
endex2345@gmail.com

Abstract

Soil organic carbon (SOC) is a significant component of soil quality, affecting fertility, structure, and resilience while playing an essential role in the global carbon cycle. Soil compaction, crust formation, the erodibility of soil and other extensive agricultural practices that result in soil degradation have a strong connection with SOC levels. Tackling these challenges requires a solid understanding of SOC dynamics and their relationship with physical soil quality indicators. This study addresses the connection between physical soil quality indicators such as compaction, crust formation, and erodibility (K-factor) and soil organic carbon (SOC) in Micro watershed level. 312 soil samples were collected from the surface layer of soil (0–20 cm) within a 1648.22 square kilometer area. Different soil properties including soil texture (Clay, Silt and Sand), pH, organic matter, bulk density, and SOC stock were analyzed. After physical analysis of these soil properties, Geostatistical tools (Interpolation Techniques) in ArcGIS were used to determine the spatial distribution. The findings showed that SOC and physical indicators has significant relationships, with higher SOC stock observed in the surface layer of soil. The areas with the highest bulk density, low SOC, and silty or sandy textures showed the most erodibility and compaction rates. The results emphasized the significance of SOC in preserving soil quality and the necessity of land effective land management practices to reduce the degradation of soil. This study establishes an approach for using geospatial tools into studies of determining the relationship of SOC and soil physical quality indicators in order to improve sustainable management of natural resources.

Keywords: Erodibility, Geospatial technologies, Soil organic carbon, Spatial distribution

Introduction

Soil organic carbon is obtained from plant and animal residues decomposed by microbes at a rate determined by temperature, moisture and other soil conditions, which is essential for most processes. Any changes in the composition and abundance of soil organic carbon have a significant impact on the number of functions on the ecosystem. It is highly linked with the expansion of soil erosion and reduction of organic carbon in the soil as onsite effect of soil erosion (Imamoglu & Dengiz, 2017). According to Sun et al. (2022), the amount, distribution, and stability of SOC are proof of the time order, spatial distribution, and human disturbance of plant communities. Soil C-Stock is a measure of an agricultural system's ability to operate sustainably. Furthermore, evaluations of the organic matter fraction stock are crucial for determining the degree of quality and effectiveness of the material that has been introduced to the soil (Nicoloso et al., 2014).

Soil quality is required for effective environmental and agriculture management, which involves determination of soil properties. Soil organic carbon (SOC) is a vital component of soil quality, affecting fertility, structure, and resilience while playing an essential role in the global carbon cycle. Soil compaction, crust formation, the erodibility of soil and other extensive agricultural practices that result in soil degradation have a strong connection with SOC levels (Mikstas & Dengiz (2023). Soil compaction is a heterogenous process caused by a change in its apparent density per unit of soil volume (Frene, 2024). According to Graves et al. (2015), soil compaction decreases plant and crop growth and yield, losing the agricultural industry more than $300 million yearly. Tackling these challenges requires a solid understanding of SOC dynamics and their relationship with physical soil quality indicators. This study investigates the relationship between soil organic carbon (SOC) at the micro watershed level and physical soil quality indicators as compaction, crust formation, and erodibility (K-factor). This work utilizes geospatial technologies into investigations into the correlation between soil organic carbon (SOC) and physical quality indicators of soil to enhance sustainable natural resource management.

Material and Methods

Area Description

The study was conducted in the Central Black Sea region of Türkiye, which is situated in the provinces of Corum and Yozgat. Alaca catchment, encompasses 1656.4 Km2. It is geographically located between 39° 55′ 0″ to 40° 15′ 0″N latitudes and 34° 32′ 0″ to 35° 20′ 0″E longitudes (Figure 1).

The catchment's geological layers are primarily composed of limestones and Mesozoic–Tertiary ophiolitic series. Quaternary alluvial and colluvial deposits, which are composed of mixed gravel elements, also occupy the low-lying regions of the alaca catchment. Mountains (particularly intermediate and low relief mountain ranges), hills, and plains characterize the study area's diverse topography, while steep slopes define the southwest and southeast regions. The elevation in the study area varies between 824 and 1275 meter above sea level. Toprak dede Tepesi which is found in the eastern portion of the basin contains the highest elevation. The mean annual precipitation and temperature in the area is found to be 364.8 mm and 9.50C (Imamoglu & Dengiz, 2017).

The majority of the basin's soils are brown (65.2%) and brown forest (9.3%). The other soil types found in the study region are distributed as follows: non-calcaric brown soil (6.3%), colluvial soil (5.9%), chestnut soil (6.4%), and alluvial soil (6.9%) (Imamoglu & Dengiz, 2017).

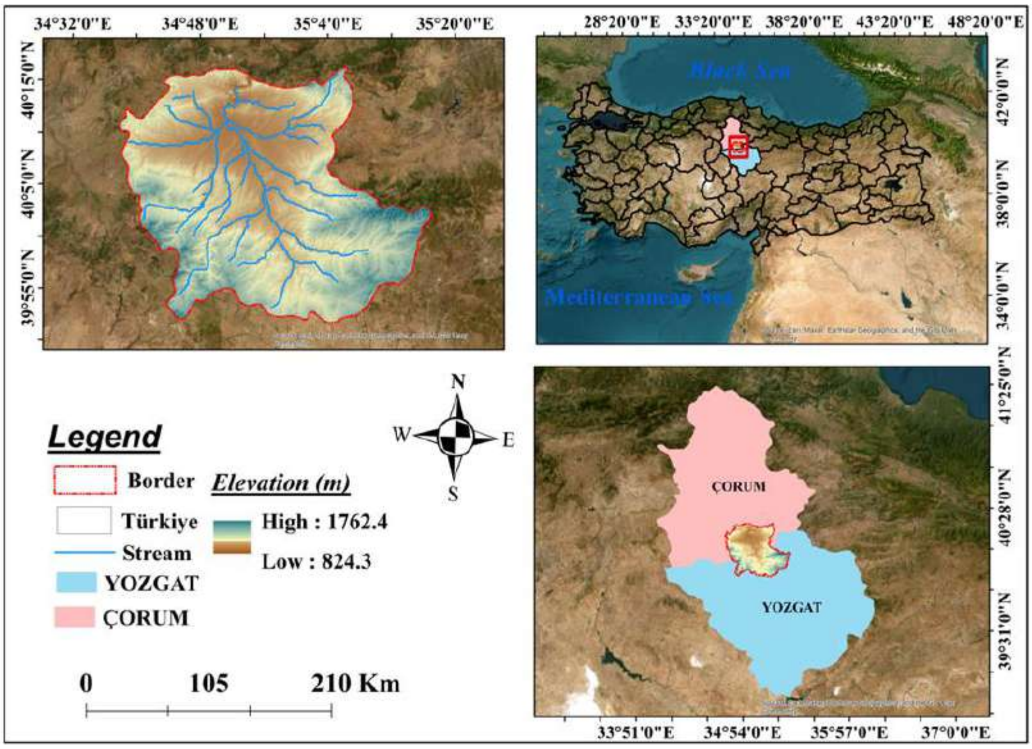


Figure 1. Location Map

Data Collection and Analysis

Soil sampling points were distributed using ArcGIS software research sample points distribution technique. 312 Soil samples were taken on the top layer of soil (0-20cm). Figure 2 shows the spatial distribution of soil sampling points. All necessary preprocessing procedures, such as drying and sieving, were carried out once those soil samples were collected. After sieving all the samples with 2mm sieve, soil quality parameters such as Soil texture (%Clay, %Silt and %Sand), Organic carbon and Bulk density was analyzed in the laboratory. The principles used in determining each soil properties are described in table 1.

Table 1. Principles of soil characteristics

Parameters	Principles	References
Organic Matter	Walkley-Black wet digestion	Nelson & Sommers (1982)
pH	Soil water suspension	Soil Survey Laboratory (1992)
Electrical conductivity	Soil water suspension	Soil Survey Laboratory (1992)
$CaCO_3$	Scheibler Calcimeter	Soil Survey Staff (1993)
Texture	Hydrometer method	Bouyoucos (1951)

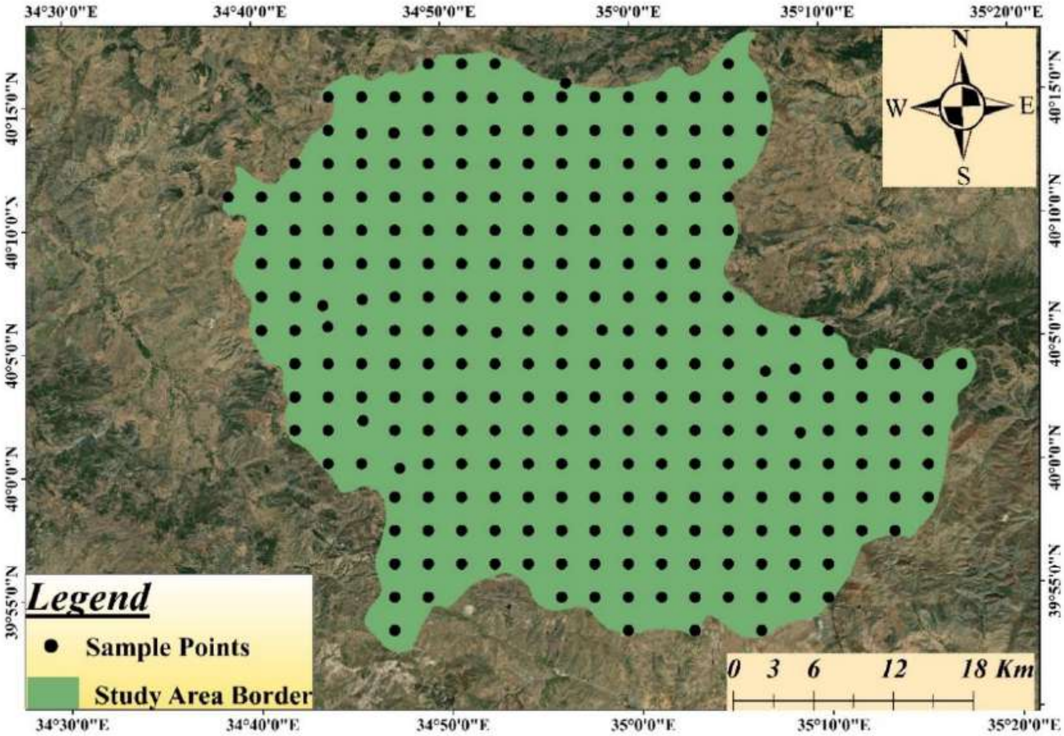


Figure 2. Soil sampling points

Soil Compaction (SC)

Modern agriculture is one of the most disrupting practices that has a lasting impact on soil processes. The chemical, physical, and biological characteristics of the soil are severely harmed by agricultural activities, which in consequence have an influence on the ecosystem services that the soil offers (Tittonell 2020: Frene *et al.*, 2024). Soil compaction susceptibility was determined by using the Vignozzi et al. (2023) index. It is linked to Smith et al. (1997)'s technique and the formula used by Pellegrini et al., (2018) to determine the ρ100kPa (Eq. 1).

$p1000kPa = 1.04231 + EXP(-0.486474 - 0.464448186*SOC)$

$SCI = -0.09266+0.01576*(Si+CI)-0.00012*(Si+CI)2 + p100kPa$

Where: SOC: Soil organic carbon (%), Si: Silt (0.002–0.05 mm) (%), Cl: Clay (< 0.002 mm) (%)

Crust Formation (CF)

The Earth's crust, one of the chemical layers, is differentiated for displaying the unique chemical characteristics found at each layer (Nawaz, 2019). The FAO (1979) crust formation index was utilized to determine the susceptibility of soil crusting (Pellegrini et al., 2018). The following equation (3) is used to determine the soil crusting susceptibility:

$$CFI = OM\ (\%) \times \frac{100}{Clay\ (\%) + Silt\ (\%)}$$

Where: CFI, Crust Formation Index, OM, Organic Matter Content

Soil Erodibility (K)

Soil Erodibility is the resistance of soil to both detachment and transportation. Which is affected by different soil properties. Based on the findings of the basic soil characteristics analysis, Wischmeier and Simith (1978) calculated the soil erodibility K-value as follow.

$K = \{0.00021 \times M1.14 \times (12\text{-}OM) + 3.25 \times (SSC\text{-}2) + 2.5\times(PSHCC\text{-}3)\}/100$

OM: Organic matter (%), SSC: Soil structure code, PSHCC: Profile saturated hydraulic conductivity code, M: Textural factor, M = (silt 0.002-0.05mm (%) + fine sand 0.05-0.1mm (%)) × (100 - clay <0.002mm (%))

Stock Soil Organic Carbon (SOC Stock)

Soil C-Stock is considered as the determinant of the effective application of an agricultural system. Evaluations of the organic matter fraction stock are also crucial for determining the effectiveness and value of the material that has been implemented to the soil (Nicoloso et al ., 2014: Freitas ., 2018; Ferreira ., 2024). Soil organic carbon was calculated using the following formula (Zhang et al. 2012).

$$SOCstock = SOC * BD * D$$

SOC: Soil organic carbon content (%), BD: Bulk density (g cm^{-3}), H: Soil depth (2 dm)

Results And Discussion

Descriptive Statistics of Soil characteristics

Table 2 shows the descriptive statistics of the soil characteristics including soil physical and chemical properties. The average percentage of soil textural classes is found to be 43.5%, 20% and 36.5% for Sand, silt and clay fractions. The mean value of bulk density is found to be 1.42 g/cm^3. The variability of soil characteristics has been assessed through the coefficient of variation (CV). Mulla and McBratney (2000) and Wilding et al. (1994) define variability as low when the CV is less than 15%, moderate when it is between 15% and 35%, and high when it exceeds 35%. The result reveals that Bulk density, Compaction and pH have lower variability, whereas clay, electrical conductivity, organic matter, hydraulic conductivity and crust formation has very high variation.

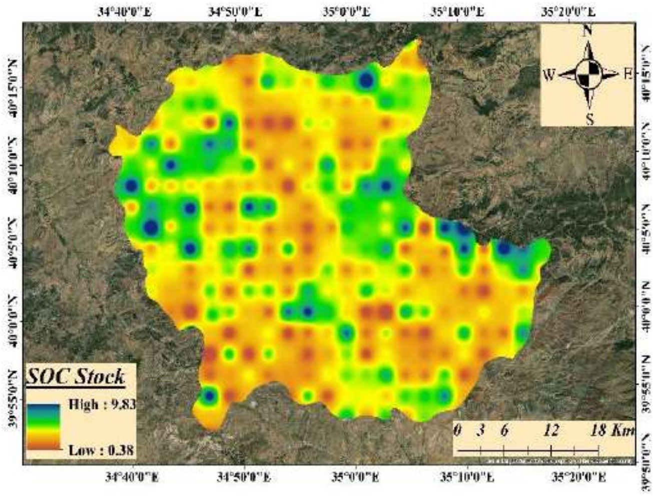
The percentage of silt, sand and soil erodibility falls on the moderate level of variation. The pH value ranges between 6.8 to 8.62. The minimum and maximum value of soil organic matter content is found to be 0.21 and 6.62 respectively.

Table 2. Descriptive statistics of soil characteristics

Soil Properties	Min	Max	Mean	SD	Variance	COV	Skewness	Kurtosis
% clay	2.74	62.82	36.50	13.28	176.36	36.38	-0.43	-0.49
% Silt	3.55	37.33	19.99	5.53	30.60	27.67	0.05	0.86
% sand	16.04	93.06	43.51	14.72	216.65	33.83	1.02	0.89
pH	6.80	8.62	8.12	0.33	0.11	4.03	-1.63	3.95
Ec(dS/m)	0.03	0.99	0.23	0.12	0.01	51.78	1.94	7.77
% CaCO3	0.00	48.53	10.30	8.37	69.97	81.24	1.35	2.81
OM %	0.21	6.62	2.42	1.17	1.37	48.36	0.88	0.72
OC%	0.12	3.84	1.41	0.68	0.46	48.36	0.88	0.72
HC cm/h	0.02	15.59	0.98	1.93	3.73	196.68	4.08	21.01
Bulk Density g/cm3	1.27	1.60	1.42	0.07	0.01	5.19	0.25	-0.67
Erodibility_K	0.00	0.14	0.09	0.03	0.00	32.03	-0.85	0.50
p1000kpa	1.15	1.62	1.38	0.09	0.01	6.85	-0.08	-0.41
Compaction Index	1.39	2.03	1.77	0.10	0.01	5.93	-0.55	0.69
Crust formation	0.41	23.83	4.69	3.10	9.61	66.07	2.71	11.23
SOCStock	0.38	9.83	3.95	17.87	319.34	45.38	0.74	0.31

Spatial Distribution of Physical Parameters

Following the analysis and calculation of the physical soil quality parameters, the spatial distribution of these parameters was determined by using Geostatistical techniques in ArcGIS. The best interpolation method was determined by comparing the value of root mean square error of all interpolation techniques. The interpolation technique with lower root mean square error is considered as accurate method of interpolation. According to the result, the amount of maximum and minimum stock organic carbon found to be 9.83 and 0.38 respectively (Figure 3). It has an average value of 3.95. The highest value of stock organic carbon is found on the lower stream area, area having gentle slope. Which is less exposed to soil erosion and it can be the result of deposition from the upslope area, area with higher slope. Soil compaction ranges between 1.39 and 2.03 (Figure 4). Soil compaction is higher in area with high bulk density.



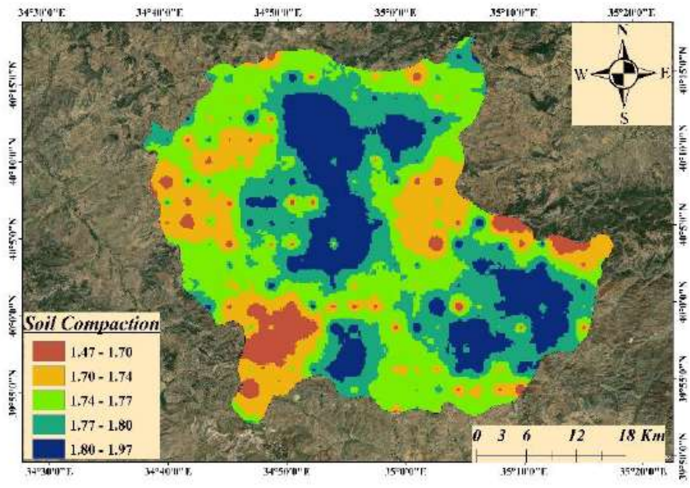
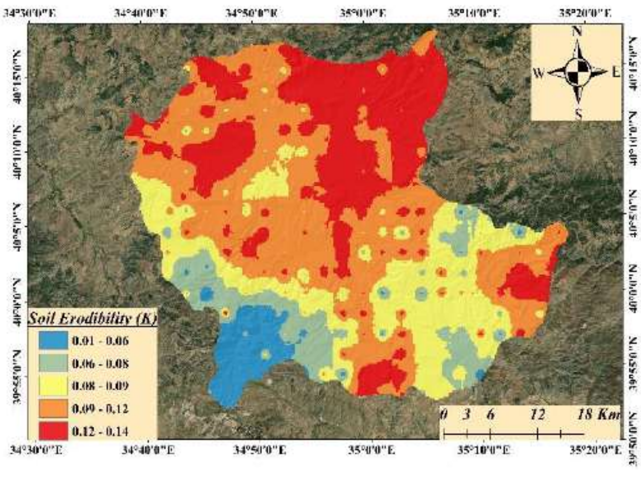


Figure 3. Soil organic carbon stock

Figure 4. Soil compaction

Soil erodibility value ranges from 0.01 to 0.14 t·ha·hr·MJ^{-1}·mm^{-1}. The northern parts of the catchment, where the river has carved out its course and runs over an alluvial plain close to the catchment center, have high soil erodibility (K) values (Imamoglu & Dengiz, 2017). Figure 5. Demonstrated the spatial distribution of soil erodibility in alaca catchment. In the study area crust formation varies 0.41 to 23.8 (Figure 6), with highest value found in the area with fine textured soil. It is the most frequently changing physical process specially on the upper portion of soil which is mainly caused by different management activities such as tillage and the impact of raindrop (Mikstas & Dengiz (2023).



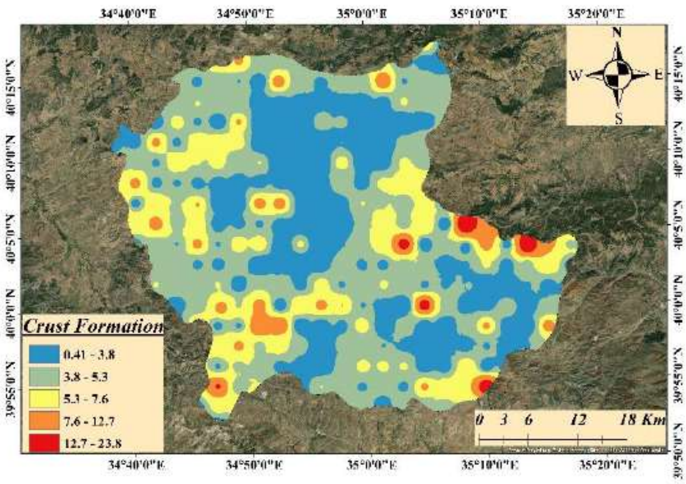


Figure 5. Soil erodibility map

Figure 6. Crust formation

Correlation Between Soil Characteristics

Figure 7 shows the correlation between soil organic carbon stock and the physical soil quality indicators. Organic matter has a significant impact in boosting soil quality positively affecting hydraulic conductivity, clay fraction and soil organic carbon stock. Soil organic carbon has negative correlation with compaction index (-0.79), it improves soil structure and reduces bulk density and soil compaction. This correlation is further supported by literature demonstrating that soil with higher organic matter has lower bulk density (Mikstas & Dengiz, 2023). Soil organic carbon has negative correlation with crust formation by improving soil structure and stability while reducing surface sealing (Oldfield et al., 2019). It has also negative correlation with soil erodibility which boost soil structure and stability, which helps protect against erosion. In accordance with Gaiser and Stahr (2013), organic matter improves soil aggregation and boosts erosive force resistance. An increased compaction index may make soil more erodible because compacted soils are more likely to erode because of greater runoff and less infiltration. Faster surface runoff and erosion rates may result from the lower porosity of compacted soils (Lal, 2001).

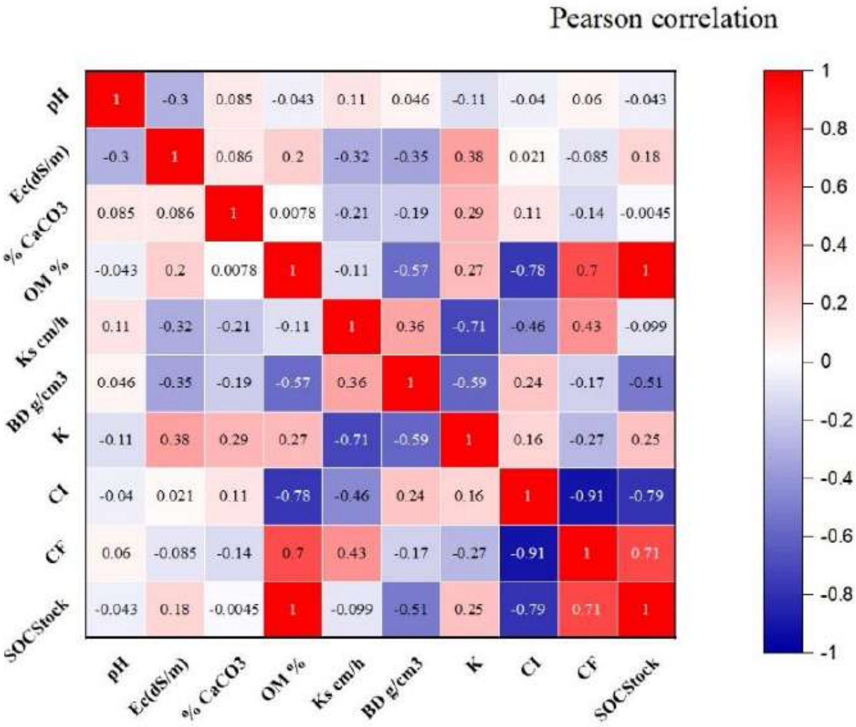


Figure 7. Correlation between soil properties

BD: Bulk Density, OM, Organic matter, SOC: Soil organic carbon, EC: Electrical conductivity, K: Erodibility , CF: Crust formation, CI: Compaction index,

Conclusion

This study examines the complicated relationships among physical soil quality indicators, such as compaction, crust formation, and soil erodibility, and soil organic carbon (SOC) in a 1,648.22 km^2 micro-watershed in the Central Black Sea region of Türkiye. 312 soil samples from the top 0–20 cm soil layer was examined in order to evaluate important characteristics such as bulk density, organic matter concentration, and SOC stock. The spatial distributions of these indicators have been calculated using ArcGIS's geostatistical tools. The average SOC stock value was 3.95 t·ha^{-1}, with values ranging from 0.38 to 9.83 t·ha^{-1}. Higher SOC areas exhibited better soil structure and less degradation. On the other hand, areas with low SOC and sandy or silty soils were more susceptible to compaction and erosion; erodibility (K-factor) values at these areas might approach 0.14 t·ha·hr·MJ^{-1}·mm^{-1}. These findings advocate for sustainable land management practices to enhance SOC stocks, protect soil resources, and promote long-term agricultural productivity and ecosystem health.

References

FAO., 1979. Soil survey investigations for irrigation. FAO Soils Bulletin 42. Food and Agriculture Organization of the United Nations (FAO), Rome. 187p. Available at [Access date: 15.08.2022]: http://www.fao.org/3/a-ar121e.pdf.

Ferreira, C.D.S., Tavares, R.L.M., Paiva Filho, S.V.D., Cantão, V.C.G., Simon, G.A., Alves, J.M., Bilego, U.O., 2024. Stock of Carbon and Soil Organic Fractions in No-Tillage and Crop–Livestock Integration Systems. *Sustainability*, *16*(7), 3025.

Freitas, L.D., Oliveira, I.A.D., Casagrande, J.C., Silva, L.S., Campos, M.C.C., 2018. Carbon stock of oxisols in natural and altered management systems. Forest Science, 28(1), 228-239.

Frene, J.P., Pandey, B.K., & Castrillo, G., 2024. Under pressure: elucidating soil compaction and its effect on soil functions. Plant and Soil, 1-12.

Gaiser, T., Stahr, K., 2013. Soil organic carbon, soil formation and soil fertility. *Ecosystem Services and Carbon Sequestration in the Biosphere*, 407-418.

Graves, A.R., Morris, J., Deeks, L.K., Rickson, R.J., Kibblewhite, M.G., Harris, J.A., Truckle, I., 2015. The total costs of soil degradation in England and Wales. Ecol Econ 119:399–413

Imamoglu, A., Dengiz, O., 2017. Determination of soil erosion risk using RUSLE model and soil organic carbon loss in Alaca catchment (Central Black Sea region, Turkey). Rendiconti Lincei, 28, 11-23.

Lal, R., 2001. Soil degradation by erosion. *Land degradation & development*, *12*(6), 519-539.

Mikstas, D., Dengiz, O., 2023. Understanding relationship between physical quality indicators and organic carbon in soils affected by long-time continuous cultivation under sub-humid ecosystem. Eurasian Journal of Soil Science, 12(3), 229-237.

Mulla, D.J., McBratney, A.B., 2000. Soil spatial variability. In: Sumner ME, editor. Handbook of soil science. Boca Raton (FL): CRS Press; p. 321–352.
Nawaz, M., 2019. Introductory Chapter: Earth Crust-Origin, Structure, Composition and Evolution. In Earth Crust. IntechOpen.
Nicoloso Denardin, R.B., Luis Mattias, J., do Prado Wildner, L., Nunes Nesi, C., Sordi, A., 2014. Carbon stock in soil under different forest formations, Chapecó, Santa Catarina state. Ciência Florestal, 24(1), 59-69.
Oldfield, E.E., Bradford, M.A., Wood, S.A., 2019. Global meta-analysis of the relationship between soil organic matter and crop yields. *Soil*, *5*(1), 15-32.
Pellegrini, A.F., Ahlström, A., Hobbie, S.E., Reich, P.B., Nieradzik, L.P., Staver, A.C., Jackson, R.B., 2018. Fire frequency drives decadal changes in soil carbon and nitrogen and ecosystem productivity. *Nature*, *553*(7687), 194-198.
Smith, C.W., Johnston, M.A., Lorentz, S., 1997. The effect of soil compaction and soil physical properties on the mechanical resistance of South African forestry soils. Geoderma 78(1-2): 93–111
Sun, T., Tong, W.J., Chang, N.J., Deng, A.X., Lin, Z.L., Feng, X.B., Li, J.Y., Song, Z.W., 2022. Estimation of soil organic carbon stock and its controlling factors in cropland of Yunnan Province. China J Integr Agric 21(5):1475–1487
Tittonell, P., 2020. Assessing resilience and adaptability in agroecological transitions. Agric Syst 184:102862.
Vignozzi, N., Andrenelli, M.C., Agnelli, A.E., Fiore, A., Pellegrini, S., 2023. Short-Term Effect of Different Inputs of Organic Amendments from Olive Oil Industry By-Products on Soil Organic Carbon and Physical Properties. *Land*, *12*(8), 1628.
Wilding, L.P., 1985. Spatial variability: Its documentation, accommodation and implication to soil surveys. In: Soil Spatial Variability: Proceedings of a Workshop of the ISSS and the SSSA, 30 November-1 December 1984. Nielsen D.R., Bouma, J. (Eds.). Las Vegas, USA, pp.166-194.
Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion loses a guide to conservation planning. United States Department of Agronomy, Agriculture Handbook No:557, Washington, USA. 163p.
Zhang, J.Y., Zhang, W.J., Xu, M.G., Huang, Q.H., Luo, S., 2012 Response of soil organic carbon and its particle-size fractions to different long-term fertilizations in red soil of China. Plant Nutr Fert Sci 18:868–875. https://doi.org/10.11674/zwyf.2012.11480

Determination of potential erosion risk status with LEAM model; A case study in micro basin

Eren ÖZEK *, Orhan DENGIZ
Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Eren ÖZEK
eren026@gmail.com

Abstract
For many regions of the world, soil erosion is one of the most important events that cause land degradation by carrying away fertile soil layers and decreasing soil fertility, reducing the amount of organic matter and nutrient element content in the soil. For this reason, erosion studies have an important place among the researches on soil. Determination of erosion risk status of soils can be done directly in field and laboratory studies, as well as indirectly by means of developed models so, risk estimations can be made especially for large areas. The aim of this study is to determine the potential erosion risk areas by using LEAM (Land Erodobility Assessment Methodology) model by using geographic information system and remote sensing techniques in micro-basin covers a 50.5 ha and located in Çorum province.
Keywords: Corum Micro-basin, Erosion, GIS and RS, Land degradation, LEAM

Introduction

Soil is defined as the mixture of rocks, minerals and organic matter that make up the Earth's crust. It is one of four elements that are necessary for life. Together with sunlight, air and water, soil is the source of life for all living things. The present and future prosperity of a society is contingent upon the sustainable use of this natural resource. However, soil is gradually being depleted as a result of inappropriate utilisation and a lack of sufficient measures to counteract natural processes. The efficient and sustainable use of soil and water resources in our country assumes greater importance when population growth is taken into consideration. One of the most significant challenges currently facing these resources is erosion. The principal factors influencing the erosion process can be categorised as follows: soil structure, topography, climate, vegetation and human activities. The climate and topographical structure of Turkey offer highly conducive conditions for the formation of erosion. As a result of factors including inappropriate land use, steep slopes and irregular rainfall, the extent of erosion is increasing annually (Ministry of Agriculture, Forestry and Villages, 1987; Bayramin et al., 2002).

The prompt and precise identification of areas affected by erosion, coupled with the formulation of effective management strategies, is of paramount importance for the long-term sustainability of land and soil resources. The integrated application of Geographic Information Systems (GIS) and Remote Sensing (RS) methodologies offers significant benefits, particularly in the context of management and conservation studies. This is due to the ability to rapidly assess the extent and severity of erosion across vast areas at a relatively low cost (Szabo et al., 1998; Sarıoğlu et al., 2011). Given the lengthy timeframes and high costs associated with classical survey methods, a range of alternative models have been developed for the assessment of erosion. For example, models such as USLE, RUSLE, EPIC, EUROSEM and CREAMS are based on field measurements, whereas models such as CORINE and ICONA offer parametric approaches (Meyer, 1980; De Graaff, 1996; Aiello et al., 2015; Tanyaş et al., 2015).

In this context, the LEAM (Land Erodibility Assessment Model), developed in the 1980s, is one of the most widely used models for the assessment of erosion risk. In a study conducted by Çakal et al. (2002), the Tortum Lake basin was mapped using GIS and UA techniques with the LEAM model, which revealed that 91% of the study area was under high risk of erosion. Similarly, Dengiz and Başkan (2006) found that 73% of the Ankara Gölbaşı Special Environmental Protection Area was at low and medium risk of erosion, while the remaining areas were at high risk. Sarıoğlu et al. (2011) employed the LEAM methodology in the Soğulca basin in the south of Ankara, demonstrating that 21.3% of the area exhibited low potential erosion risk, 49.5% demonstrated high potential erosion risk, and 28.2% demonstrated very high potential erosion risk.

The aim of this study is to ascertain the potential erosion risks in the Çorum micro-basin, situated in the Central Anatolia Region of Turkey, through the utilisation of the LEAM model. Furthermore, the risks will be mapped using GIS and UA techniques. The objective of this study is to provide insights that will inform the development of effective erosion management strategies for the region.

Material and Methods

The research area is a 50,515.4 ha micro basin located in the south east of Çorum province. The average annual precipitation is 443.7 mm and the average annual temperature is 10.7 °C. The minimum elevation of the basin is 950 m and the maximum elevation is 1762 m. The surface water resources in the study area are Büyüköz stream, Eymir, Kırım, Sarımbey, Ağabayır, Kaynarca streams and the total length of waterways is 179 km.

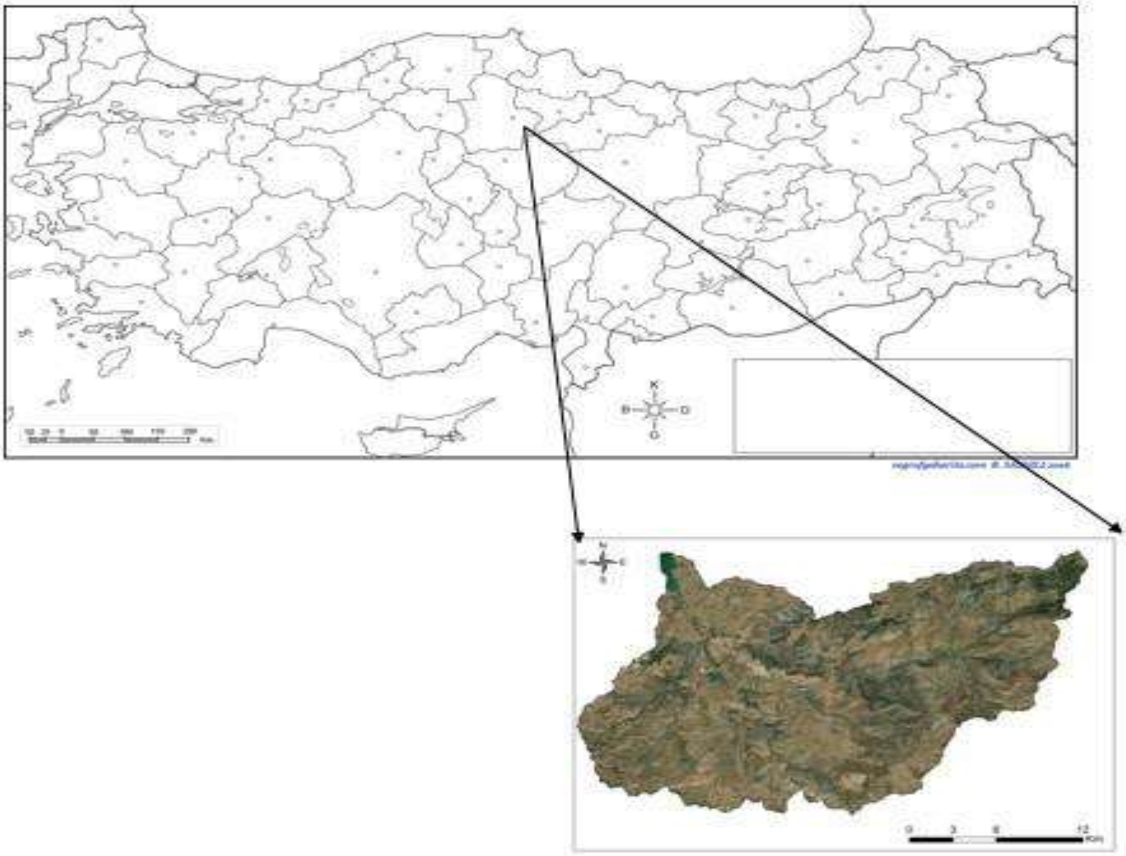


Figure 1. Location map of the study area

Table 1. Meteorological data for the study area

	January	February	March	April	May	June	July	August	September	October	November	December	Yearly
T (°C)	-0,3	1,1	5,2	10,5	14,9	18,5	21,2	21,1	17,1	11,8	5,9	1,8	10,7
P (mm)	39,5	30,3	39	51,5	60,9	54,9	19,2	15,3	23,5	29,4	35,5	44,7	443,7

T: Mean temperature, P: Total precipitation

The LEAM (Land Erosion Assessment Model) is one of the models employed in the assessment of potential erosion risk (Manrique, 1988). In accordance with the model, an erosion susceptibility assessment is predicated on three fundamental land characteristics. The aforementioned terrain characteristics are as follows: The three basic land characteristics are slope hazard (S), rainfall erosion risk (RR) and soil erosion susceptibility (K). The slope hazard was determined with the assistance of a topographic map, the rainfall erosion risk was gauged using the Fournier Index, and the soil erosion susceptibility was calculated using the erodibility formula (Wischmeier and Smith, 1978). Figure 2.

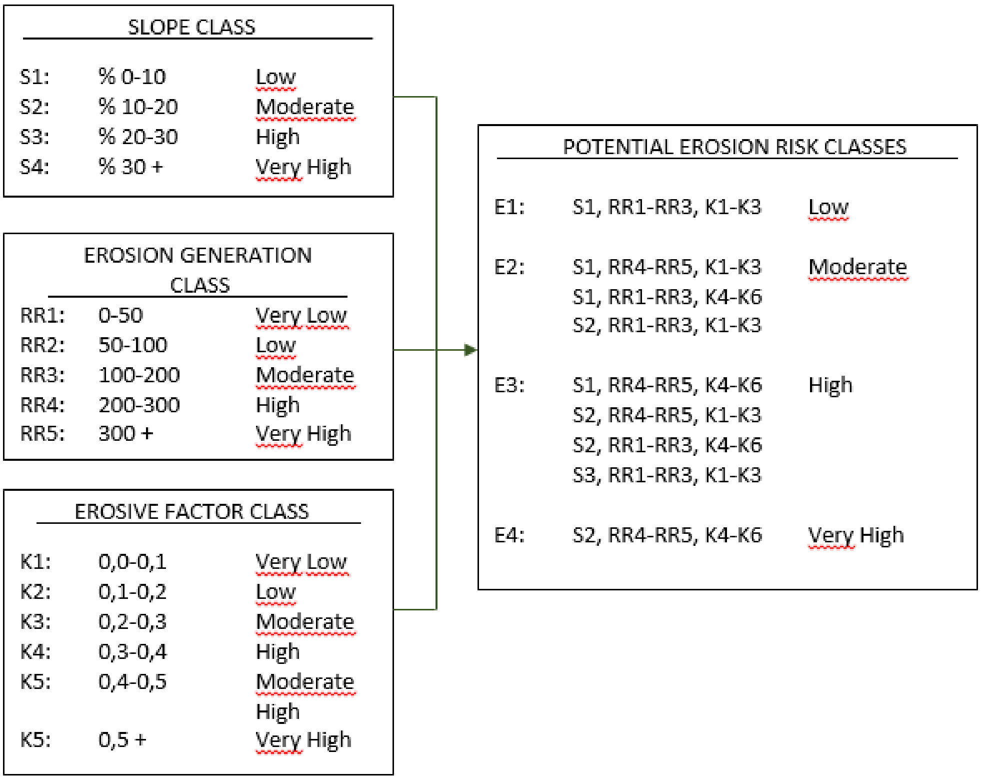


Figure 2. LEAM erosion model flow diagram

The initial step involved the production of a digital elevation model (DEM), which was created by digitising the 1:25,000 scale topographic map of the study area within a geographic information system (GIS) environment (Figure 3). The DEM map was used as the basis for the creation of slope, aspect and elevation maps of the area.

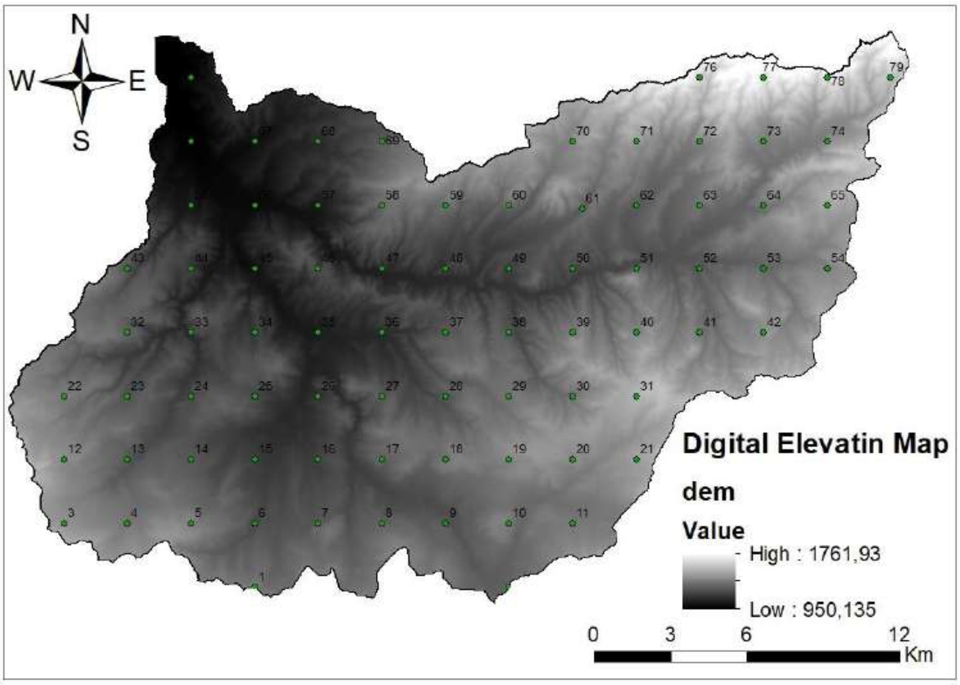


Figure 3. Digital elevation model (DEM) map of the study area.

In the second stage, the Fournier index is employed for the purpose of determining the erodibility characteristics of soils. The index considers the quantity and intensity of precipitation, as well as the meteorological characteristics of the region in question. The following formula is employed for the calculation of the index.

$$FI = \sum_{i=1}^{12} \frac{Pi^2}{\overline{P}}$$

In this instance, the value of pi is as follows: The total precipitation for the specified time period is represented by the variable P, which is also used to denote the average annual precipitation.

In the final stage of the study, 79 surface soil samples were collected from within the boundaries of the basin. These samples were used to determine the susceptibility of the soil to erosion (erodobility factor) and to create a map of the distribution of K (erodobility factor) in the micro-basin. This map was created using a geostatistical method, and the resulting map is presented in Figure 4.

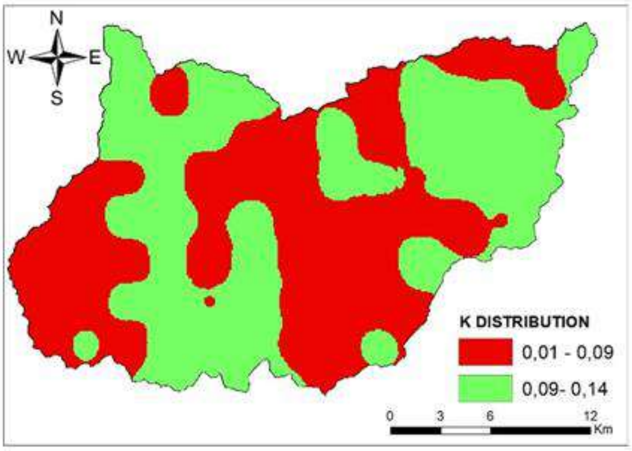


Figure 4. K Distribution Map

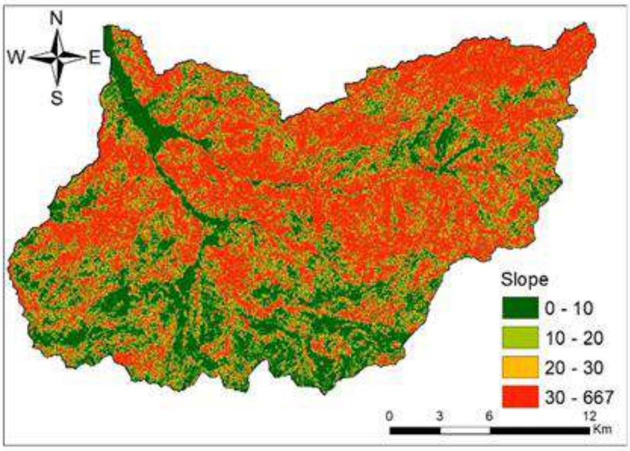


Figure 5. Slope Map

Results And Discussion

The initial parameter employed in the LEAM model is the slope parameter. The slope classification is divided into four classes within the LEAM model. Areas with a slope between 0 and 10% are classified as low, areas with a slope between 10 and 20% are classified as medium, areas with a slope between 20 and 30% are classified as high, and areas with a slope of more than 30% are classified as very high. Approximately 27% of the micro-basin is comprised of areas with a slope below 10%, 20% of the micro-basin is comprised of areas with a slope between 10-20%, and 53% of the micro-basin is comprised of areas with a slope of 20% and above, which is defined as very high. Another parameter employed in the model is climate (erosivity), which represents the impact of precipitation on erosion and is calculated according to the modified Fournier Index equation. According to the Fournier Index, the erosivity was determined to be very low and classified as 1st class with a value of 42,04.

The final step in the LEAM model for determining the potential erosion risk is to ascertain the erodibility classes of the soils in question. In accordance with the model, the erodibility (erodobility) of the basin was ascertained through the utilisation of the equation devised by Wischmeier and Smith (1978), incorporating parameters such as soil texture, soil permeability, organic matter and structure, in 79 surface soils extracted from the study area. The erodibility values (K) were determined by geostatistics, and a K distribution map was created and presented in Figure 4. The K classes thus determined are classified into five categories, as follows: very low (0.0-0.05), low (0.05-0.1), medium (0.1-0.2), high (0.2-0.4) and very high (0.4-0.6).

Ultimately, the potential erosion risk map was created according to the LEAM model by combining the Fornier index, slope and K factors in a GIS environment, thus providing a comprehensive representation of the area's erosion risk. A total of 13% of the area is classified as belonging to the high erosion risk class E3, while 40% is classified as belonging to the very high class E4. Figure 6 illustrates that only 47% of the area is classified as low and medium.

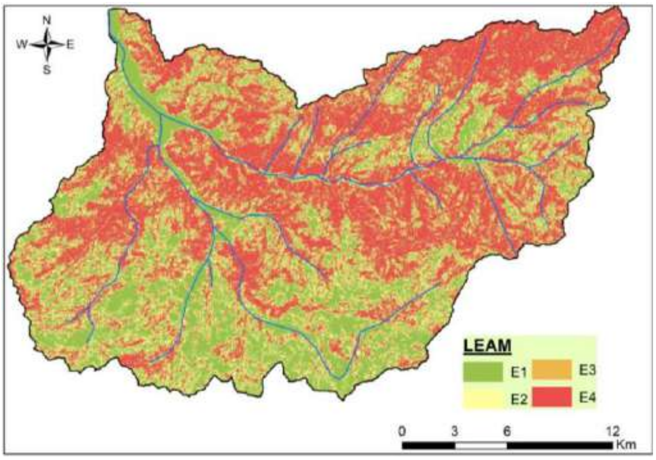


Figure 6. Erosion risk distribution map of the basin according to LEAM model.

Conclusion

Soil erosion represents a significant factor in the process of land degradation and is therefore a prominent topic of research within the field of soil science. A plethora of models, encompassing a multitude of scales and typologies, have been devised for the purpose of determining erosion and sediment delivery from past to present. Furthermore, the advancement of computers in terms of hardware and software, coupled with the rapid developments in technologies such as GIS and UA, and the products of these developments, occupy a significant position in erosion research and the development of models. Furthermore, it is recognised that GIS and UA techniques are of significant value in determining land use and land cover, which is one of the most dynamic elements on Earth. They facilitate the monitoring of changes and the determination of their effects on erosion. Given that the objective of watershed management is to guarantee the sustainability of soil and water resources, it is evident that erosion mapping is not an end in itself but rather a crucial instrument in the field of watershed management. It is therefore evident that these maps represent a crucial element in the assessment of the financial implications of watershed management initiatives and the identification of appropriate soil protection measures for the designated areas. The principal objective of the study is to ascertain the potential erosion risk areas by employing the LEAM (Land Erodobility Assessment Methodology) model in conjunction with a geographical information system and remote sensing techniques over a micro-basin of 50,515.4 Ha situated within the Çorum region. Furthermore, soil samples were collected from the basin and subjected to an erosion susceptibility index analysis, with the objective of determining the susceptibility of the basin soils to erosion. The results obtained from the model indicate that the lands in the micro-basin are subject to a high risk of erosion. In light of the aforementioned characteristics, namely the high slope of the basin, its fragmented and rugged topography, and the abrupt changes in slope over short distances, coupled with the fact that the majority of the micro-basin's forest areas have been transformed into agricultural and pasture lands as a consequence of human activities, it is evident that the basin's soils are facing significant risks.

References

Aiello, A., Adamo, M., Canora, F., 2015. Remote sensing and GIS to assess soil erosion with RUSLE3D and USPED at river basin scale in southern Italy. Catena, 131: 174-185.

Bayramin, İ., Dengiz, O., Başkan, O. Parlak, M., 2003. Soil Erosion Assessment with Icona Modele Case Study: Beypazarı Area. Turkish Journal of Agriculture and Forestry 27 (2); 105-116.

Anonymous, 1992. Corine (Commission of the European Communities). Soil Erosion Risk and Important Land Resources, Luxembourg.

Anonymous, 1999. Soil Survey Staff, Soil Taxonomy. A Basic of Soil Classification for Making and Interpreting Soil Survey. U.S.D.A Handbook No: 436, Washington D.C.

De Graaff, J., 1996. The Price of Soil Erosion: An Economic Evaluation of Soil Conservation and Watershed Development. Landbouwuniversiteit Wageningen (LUW).

Dengiz, O., Akgül, S., 2005. Soil erosion risk assessment of the Gölbaşı environmental protection area and its vicinity using CORINE model. Turkish Journal of Agriculture and Forestry, 29(6): 439-448.

Dengiz, O., Yakupoğlu, T., Başkan, O., 2009. Soil erosion assessment with qualitative approach using GIS & RS; Case study: Ankara-Güvenç Basin. Journal of Environmental Biology, 30(3): 339-344.

Genç, Z., Dengiz, O., 2015. Madendere havzasında fizyoğrafik faktörlerin ve bazı fiziko-kimyasal toprak özelliklerinin belirlenmesi ve haritalanması. Türkiye Tarımsal Araştırmalar Dergisi, 2(1): 28-39.
Hudson, N., 1986. Soil Conservation. Cornell University Press.
Manrique, L.A., 1988. LEAM. Land Erodibility Assessment Methodology. Using soil survey data based on soil taxonomy. Editorial and Publication Shop, Honolulu, Hawaii, USA.
Meyer, L.D. 1980. Soil Conservation Problems and Prospects. Ed. R.C.P. Morgan. International Conference on Soil Conservation, the Natural College of Agricultural Engineering, Silsoe, Bedford, UK.
Ministry of Agriculture, Forestry and Villages, 1987. General Management Planning of Turkey (Soil Conservation Main Plan), Ministry of Agriculture, Forestry and Villages. General Directorate of Rural Services, pp: 105. Ankara.
Sarıoğlu, F.E., Dengiz, O., Başkan, O., 2011. Potansiyel erozyon risk alanlarının belirlenmesinde LEAM modeli pilot alan: Haymana-Soğulca havzası. Ulusal Toprak ve Su Sempozyumu, 25-27 Mayıs, Ankara, s. 223-229.
Sazbo, J., L. Pasztor, Z. Suba and G. Varallyay. 1998. Integration of remote sensing and GIS techniques in land degradation mapping proceedings of the 16th International Congress of Soil Science, Montpellier, France, 20-26 August, 63-75.
Tanyaş, H., Kolat, Ç., Süzen, M.L., 2015. A new approach to estimate cover-management factor of RUSLE and validation of RUSLE model in the watershed of Kartalkaya Dam. Journal of Hydrology, 528: 584-598.
Vrieling, A., 2006. Satellite remote sensing for water erosion asessment: A review. Catena, 65(1): 2-18.
Wischmeier, W.H., Smith, D.D., 1978. Predicting Rainfall Erosion Losses. USDA Agricultural Handbook No. 537, Washington D.C.

Effects of Zn application on wheat under drought stress condition

Esther Chidinma CHUKWU [1,2,*], Coşkun GÜLSER [2]
[1] Agricultural University Plovdiv, Plovdiv, Bulgaria
[2] Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Esther Chidinma CHUKWU
esther.chukwu.191799@unn.edu.ng

Abstract

While drought stress poses a significant challenge to the growth of wheat plants, zinc (Zn) as a micronutrient plays numerous roles in supporting wheat growth and development. However, Zn must be present in optimum amounts in the soil to be effective. Understanding the role of Zn application on wheat plants under drought stress conditions can help identify possible strategies for managing wheat cultivation during drought, improving its quality and yield. Nevertheless, research on the impact of Zn on wheat under drought stress remains limited. This review's main objective is to explore wheat's anatomy, the effects of drought stress on wheat plants, the role of Zn application under drought stress conditions, and mechanisms of Zn-induced tolerance. The secondary data for this review were obtained from existing research findings sourced from Scopus, web of Science, Google Scholar, and ResearchGate. The review revealed the following key points; the major anatomical features of wheat – including its root systems, stem, leaves, inflorescence, spikelet, grain, and reproductive structures - are significantly affected by drought. Drought stress causes reduced germination and seedling growth, stunted vegetative growth, decreased grain size and yield, lower protein and nutrient content, and physiological and biochemical changes that impair overall plant health. Zn application has been shown to mitigate many of the adverse effects of drought stress. It benefits the below- and above-ground parts of the wheat plant. Zn enhances plant resilience to drought through physiological, biochemical, and molecular mechanisms. These include improved nutrient uptake, enhanced antioxidant activity, better water use efficiency, and regulation of stress-responsive genes. The findings suggest that incorporating Zn into wheat cultivation - either through foliar sprays or soil applications- can significantly enhance the growth and resilience of wheat plants under drought conditions. Future research should focus on identifying the optimal Zn application rates, methods, and timing tailored to drought-prone environments to maximize its beneficial effects on wheat production.

Keywords: Wheat, Drought, Zinc, Anatomy

Introduction

Wheat is one of the most important staple crops globally, providing a substantial portion of calories and protein for human consumption (Lalarukh et al., 2022). Although it offers enormous economic and industrial benefits, the yield, grain protein, and mineral concentration may wane due to changing climatic circumstances (Ben et al., 2021). Of all abiotic stresses, drought is regarded as the most damaging. Drought, a stress factor exacerbated by climate change, persistently endangers wheat productivity. Drought is an extended period with little to no rainfall, significantly reducing soil moisture and water availability. The season is often accompanied by higher-than-normal temperatures, increasing evaporation rates, and exacerbating water shortages. Plants lose more water through transpiration due to higher temperatures, and the soil loses water through evaporation, compounding the dryness. The air tends to be drier, with lower humidity levels, further reducing environmental moisture. Plants may wilt, show stunted growth, or die off due to insufficient water, prompting reduced agricultural productivity. Drought stress besides limiting water availability also disrupts essential physiological and biochemical processes in plants, leading to reduced growth and yield. Due to the projected rise in the frequency and intensity of drought events, it is critical to research ways to enhance wheat resilience to water scarcity.

Nutrient management emerges as a promising universal remedy to counterbalance the negative impacts of changing climatic conditions on wheat cultivation (Melash and Ábrahám, 2022). Through tailored nutrient management strategies, farmers and agronomists can contribute to sustainable wheat production, ensuring food security and maintaining the economic viability of the crop under changing climatic conditions (Melash et al., 2023). Under drought stress and associated challenges in wheat crops, zinc-containing fertilizers have been documented to effectively alleviate the inhibitory effects of abiotic stressors (Ma et al., 2017). Zn is an essential micronutrient involved in a wide variety of physiological processes. Its uptake, although varying among plant species, is determined by the composition and concentration of the growth media. Zn uptake arises as a divalent cation or as complexes with organic ligands and tends to display a linear pattern with its concentration in the nutrient solution or the soils. Within plants, Zn affects water uptake and transport and reduces the adverse effects of short heat periods or salt stress. Zn application alleviated yield reduction caused by water stress (Fatemeh et al., 2024).

This study aims to evaluate the relationship between Zn applications and their effect on wheat plants during drought stress by understanding the best cultural practices to produce high-quality grain with good protein content and overall yield.

Effects of Drought Stress on Wheat

Wheat is mainly affected by drought stress during tillering, jointing, booting, an-thesis, and grain filling stages. Drought stress during the early stages can hinder seed germination and initial root and shoot development, leading to poor crop establishment (Fig 1). In responding to drought stress, plants maintain optimum water content mainly by osmotic adjustment (Reza, 2024). Limited water availability affects cell division and elongation, resulting in stunted growth and reduced biomass (Kheradmand et al., 2014). The leaves may be smaller, fewer, and less green due to reduced chlorophyll content. Drought stress reduces the opening of stomata to conserve water, which limits the uptake of CO2 and hampers photosynthesis. This leads to reduced carbohydrate production necessary for growth and development. Drought can also cause oxidative stress, damaging chlorophyll and reducing the plant's photosynthetic efficiency (Arbona et al., 2013). Wheat plants under drought conditions may develop deeper or more extensive root systems as an adaptive mechanism to search for water deeper in the soil profile. However, severe water stress can still limit root growth and function. Water stress can delay flowering and affect the development of reproductive organs, leading to fewer flowers and, consequently, fewer grains. Drought during the flowering stage can result in poor pollination, reducing the number of grains per spike. One of the most significant effects of drought is a reduction in grain filling, leading to smaller grains. Water stress limits the plant's ability to transport and accumulate nutrients and starch in the developing grains (Kheradmand et al., 2014). Overall grain yield can be severely affected due to reduced spikelet number, fewer grains, and smaller grain size. Drought stress affects the plant's ability to take up and transport nutrients from the soil, leading to deficiencies that can further impede growth and productivity (Parkash and Singh 2020). For example, nitrogen and potassium uptake can be particularly affected. Drought stress can affect the protein content and nutritional quality of wheat grains. The synthesis and accumulation of proline were triggered when water was applied up to the tillering stage compared to when water was applied at the mid-stem elongation stage and grain filling stage (Reza, 2024). In some cases, protein content may increase slightly due to the concentration effect, but the overall grain quality can be compromised. Drought triggers the production of reactive oxygen species (ROS), which can damage cell membranes, proteins, and DNA (Arbona et al., 2013). Plants produce antioxidants to combat this stress, but severe drought can overwhelm the defense systems. Wheat plants may produce osmoprotectants (like proline and sugars) that help maintain cell turgor

under water-deficit conditions. However, as an energy-intensive process, it can divert resources from growth and reproduction. Drought stress can lead to the early aging and death of leaves and other plant parts as a survival mechanism. This premature senescence can reduce the plant's ability to photosynthesize and support grain filling, affecting overall productivity.

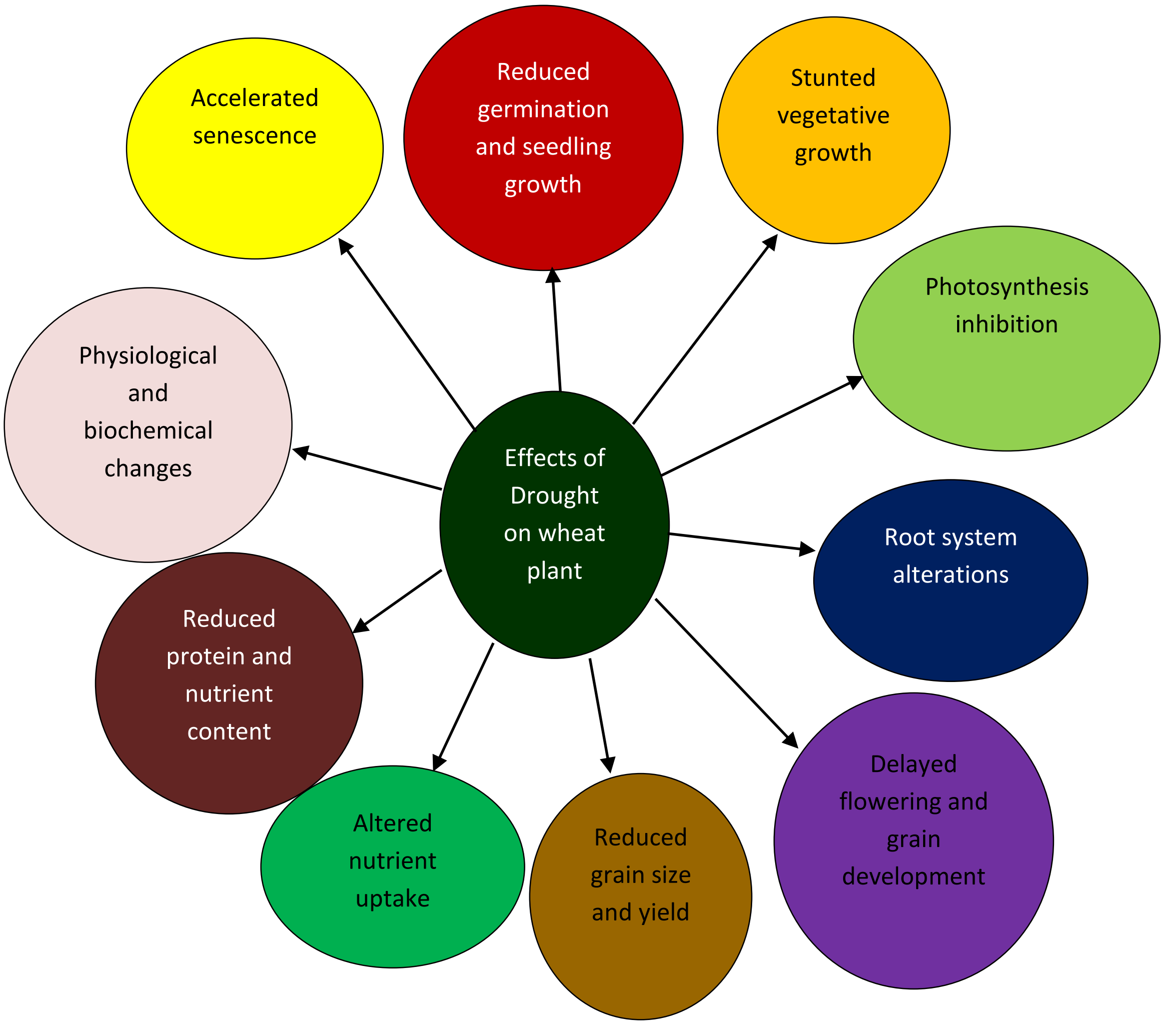


Figure 1. Effects of drought on wheat plant

Zn as an Essential Heavy Metal

Zn plays a great role in wheat production, influencing various physiological and biochemical processes essential for plant growth and development. Zn is important for chlorophyll production, which impacts the plant's ability to photosynthesize and convert sunlight into energy. The Zn application increases the plant chlorophyll, carotenoid content, and dry matter yield (Basit and Hussain, 2024). Adequate Zn availability improve root development allowing the wheat to absorb water and nutrients more efficiently. It also supports grain filling and the overall development of the wheat plant, leading to increased yield and better-quality grains. Zn is important for grain quality, contributing to the nutritional value of wheat. It plays a role in protein synthesis and accumulation of micronutrients within the grain, improving nutritional profile, which is particularly important for human consumption. Kumar et al noted that applications of 10.0 kg Zn/ha per year produced higher grain size and straw. Zn addition improved tillering and increased the grain yield of durum wheat but reduced the protein probably due to biological dilution when yield. Seeds in Zn-deficient soil produced weak plants with inferior-quality sprinkled grains and lower zinc concentrations (Yilmaz et al. 1998). Additionally, it improves the antioxidant defense mechanism of plants (Banerjee et al., 2023). Zn enhances the plant's ability to withstand environmental stresses, like drought or temperature fluctuations. It strengthens the plant's immune system, reducing susceptibility to diseases and pests. Zn is a vital component of several enzymes involved in carbohydrate metabolism, protein synthesis, and growth regulation. It acts as a cofactor and regulates the activity of several enzymes in crop plants. It activates enzymes that aid energy production and are crucial for chlorophyll and nucleic acid synthesis. Zn is a structural component of the ribosome and is essential for its structural integrity. In the absence of Zn, ribosomes degrade but can regenerate once the supply of Zn is restored. Generally, a decrease in membrane integrity, susceptibility to heat stress, decreased synthesis of carbohydrates, decreased cytochrome and nucleotide synthesis, decreased auxin synthesis, decreased chlorophyll synthesis, and inhibition of Zn enzymes are observed in plants grown on zinc-deficient soils (Marschner 1995).

The implication of Zn Application under Drought Stress

Wheat cultivars developed larger mesophyll cells, xylem tissues, bundle sheaths, and vascular bundles when drought stress was imposed on them. The vascular bundles will facilitate faster water and mineral salt movement from the root to the shoot (Fig 4C) (David et al., 2017; Mannan et al., 2022). Zn promotes the growth of roots, making them more extensive and efficient at absorbing water. This helps plants access water more effectively, even under limited moisture conditions. Modern wheat maintained better water balance and better-preserved cell membrane stability supported by a significantly low injury index under drought stress. They discovered a correlation between morpho-anatomical traits in control plants and drought-tolerant related traits which showed that the higher the leaf dissection index (i.e. more oblong leaves), the greater the water loss and the leaf membrane damages after desiccation were. Zn application can help regulate stomatal function (tiny pores on leaves), reducing excessive water loss through transpiration. This improves water use efficiency, which is critical during drought (Fig 4A). Zn application can lead to higher Zn content in wheat grains, which is beneficial for human nutrition. Drought can often affect grain quality, but adequate Zn supply helps maintain quality and quantity (Fig 3). Protein synthesis which ensures good yield with better nutritional profiles is also enhanced through the Zn application (Fig 5D) (Xu et al., 2008; Mannan et al., 2022). Zn application can enhance the antioxidant system, reducing oxidative stress and minimizing cellular damage, thus improving plant resilience under drought conditions (Reddy et al., 2004). The chlorophyll levels can also be maintained by Zn application under drought stress, this ensures efficient photosynthesis and energy production under stress (Ahanger et al., 2016) (Fig 5A-C). Drought can affect hormone balance, leading to reduced growth. Zn supplementation can promote auxin production, supporting better growth and development even under adverse conditions (Waraich et al., 2011). Zn forms synergism with macronutrients, as drought can impair nutrient absorption.

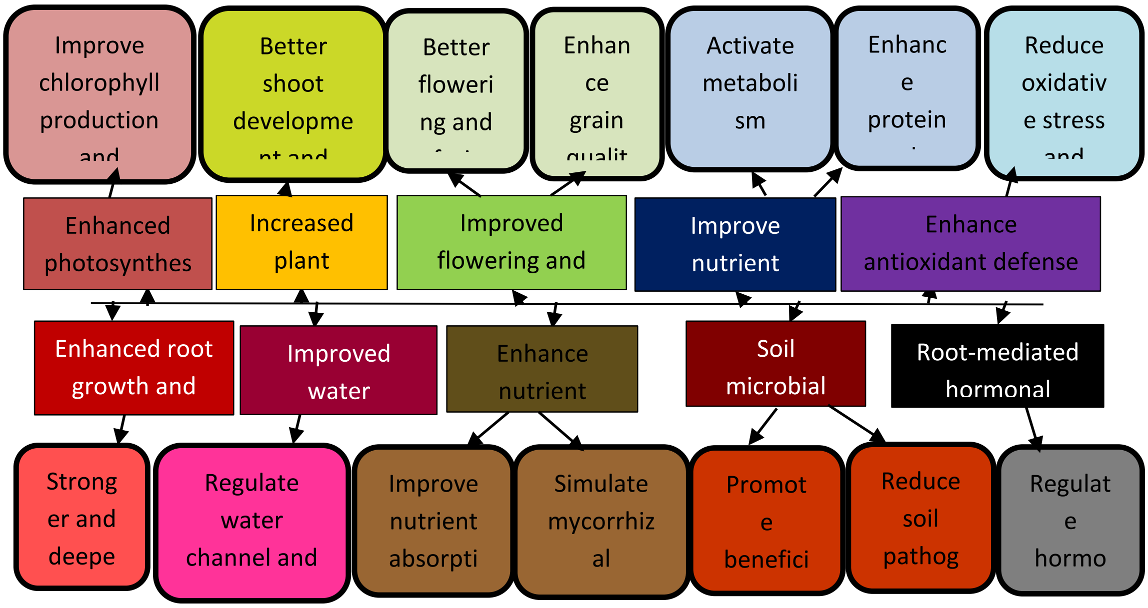


Figure 2. Below-ground and above-ground benefits of zinc application

Table 1. Below-ground and above-ground benefits of zinc application

Treatment	Spike length (cm)	Number of spike plant^{-1}	1000-grain weight (g)	Grain yield plant^{-1} (g)	Biological yield plant^{-1} (g)
WW	11.14^{a}	3.42^{a}	54.10^{a}	35.89^{a}	56.10^{a}
DS	9.01^{e}	1.39^{f}	41.63 g	10.85^{c}	17.55^{e}
Zn-Soil	9.75^{d}	1.76^{e}	43.53^{f}	11.13^{c}	18.25^{de}
Fe-Soil	9.82^{d}	1.89^{de}	44.93^{e}	11.28^{c}	18.61^{de}
(Zn + Fe)Soil	9.87^{cd}	2.03^{cd}	46.80^{d}	11.29^{c}	18.86^{d}
Zn-Foliar	10.01 cd	2.06^{c}	48.37^{c}	14.97^{b}	23.26^{c}
Fe-Foliar	10.18^{c}	2.14^{c}	49.17^{c}	15.06^{b}	23.54^{c}
(Zn + Fe)Foliar	10.53^{b}	2.45^{b}	51.60^{b}	16.09^{b}	25.21^{b}

Means followed by distinct letters differ significantly by Tukey's HSD at $p < 0.01$

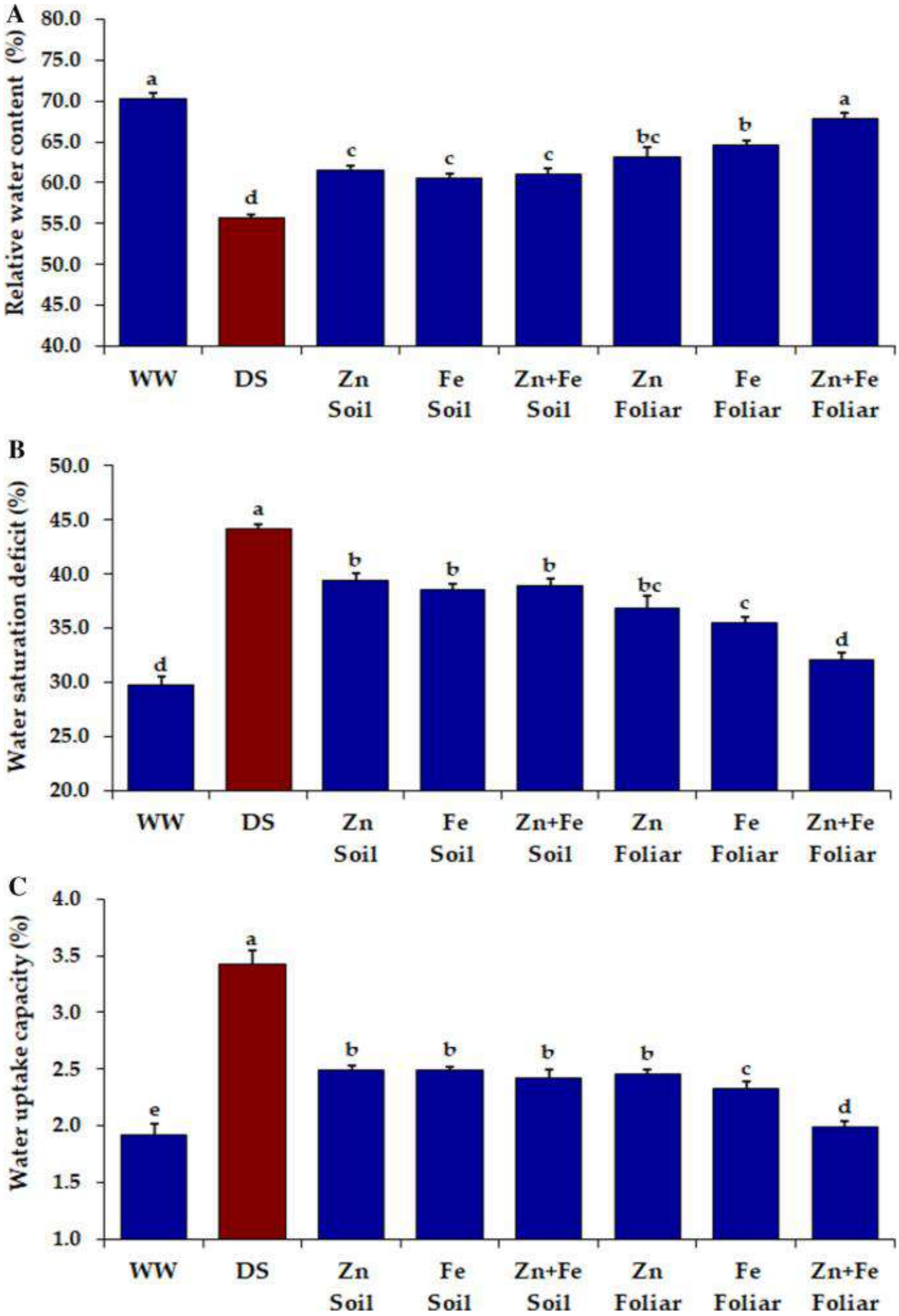


Figure 3: Impact of zinc sulfate on relative water content (a), water saturation deficit (b), and water uptake capacity (c) of wheat under water deficit conditions. The bars on the columns represent SE, and distinct letters differ significantly by Tukey's HSD ($p < 0.01$) (Mannan et al., 2022)

Mechanisms of Zn-Induced Drought Tolerance

Zn-induced drought tolerance involves a combination of physiological, biochemical, and molecular mechanisms that enhance plant resilience (Fig 6). Under drought stress, plants produce excessive reactive oxygen species (ROS) like superoxide radicals, hydrogen peroxide, and hydroxyl radicals, leading to oxidative stress and cellular damage. Zn is a cofactor for antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD) (Reddy et al., 2004). Zn application boosts the activity of these enzymes, which scavenge ROS, reducing oxidative stress and preventing damage to cellular components, such as lipids, proteins, and DNA. Zn is responsible for abscisic acid (ABA) production, which regulates stomatal opening and closure (Khan et al., 2003). The hormone plays a key role in drought response by enhancing stomatal regulation that reduces water loss through transpiration, allowing plants to conserve water. This improves water use efficiency, enabling plants to maintain physiological processes with less water. When drought stress causes lipid peroxidation and leads to cell membrane damage, Zn helps stabilize cell membranes by reducing lipid peroxidation through its role in the antioxidant defense system (Sreenivasulu et al., 2000). Maintaining membrane integrity ensures the proper functioning of cellular processes, nutrient transport, and ion balance, all critical for plant survival under drought conditions. It also influences the function of various membrane transport proteins responsible for the uptake of essential nutrients, including nitrogen, phosphorus, and potassium.

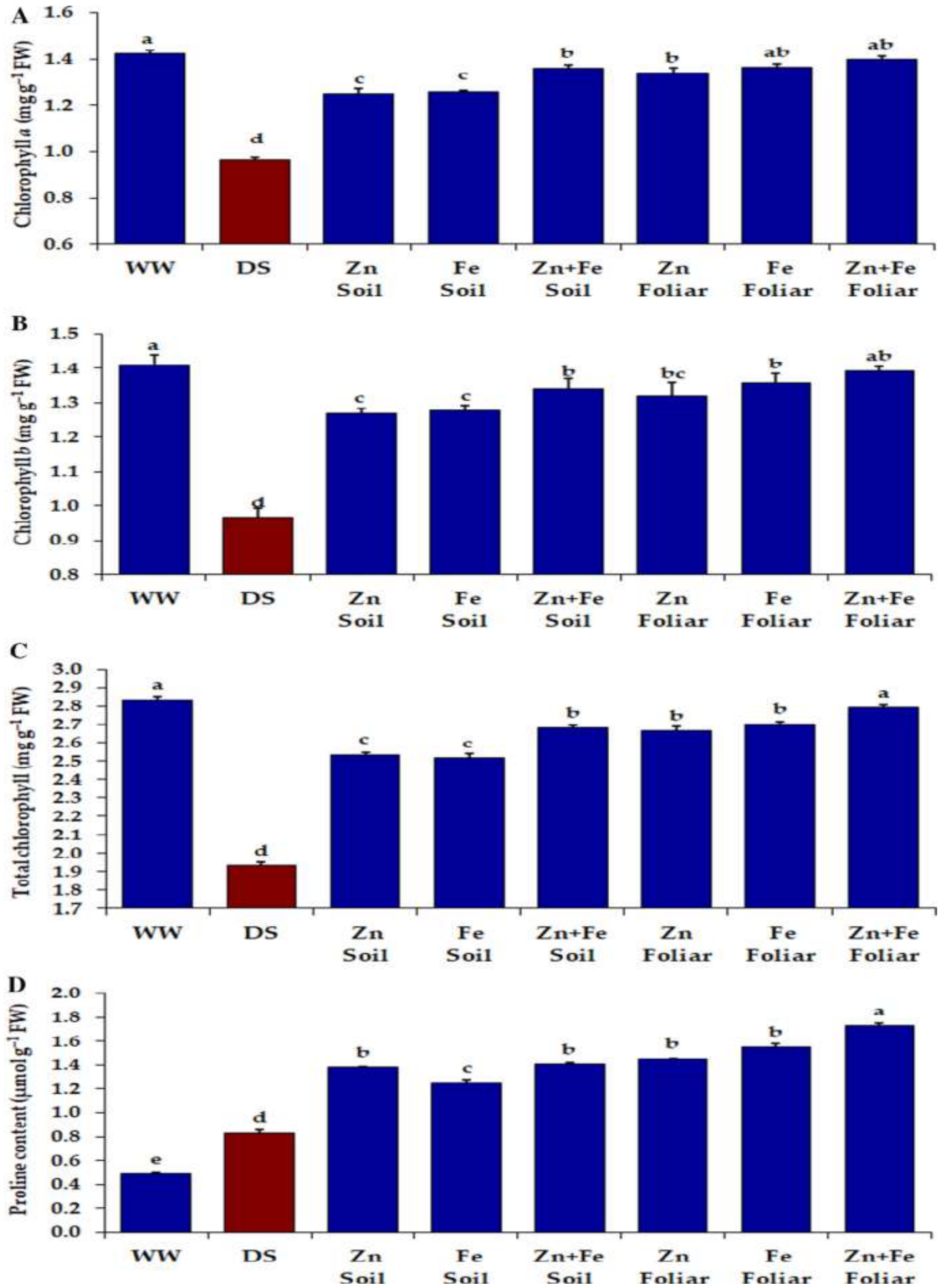


Figure 4. Impact of zinc sulfate on the content of chlorophyll a (a), content of chlorophyll b (b), total chlorophyll content (c), and proline content (d) of wheat under water deficit conditions. The bars on the columns represent SE, and distinct letters differ significantly by Tukey's HSD ($p < 0.01$) (Mannan et al., 2022)

Zn supports the synthesis of key enzymes involved in the photosynthetic pathway (Ahanger et al., 2016). Its application helps maintain chlorophyll content and enhances photosynthetic efficiency under drought stress, ensuring adequate energy production for plant growth and development. Its ability to regulate gene expression related to stress response enables the activation of the transcription of genes that encode protective proteins, stress-responsive enzymes, and antioxidants. This molecular-level regulation helps plants quickly adapt to drought stress by enhancing their physiological and biochemical responses, promoting overall drought tolerance. Zn helps regulate the accumulation of osmoprotectants like proline, soluble sugars, and amino acids, which maintain cell turgor by balancing the osmotic pressure (Xu et al., 2008). Improved osmoregulation helps plants retain water and maintain cellular functions, even under water-deficit conditions. Zn is involved in plant hormones such as auxins, gibberellins, and cytokinin synthesis and regulation, which regulate root development and influence plant growth and stress responses (Waraich et al., 2011). Its application helps maintain hormonal balance under drought stress, promoting growth processes and mitigating the adverse effects of stress on plant development.

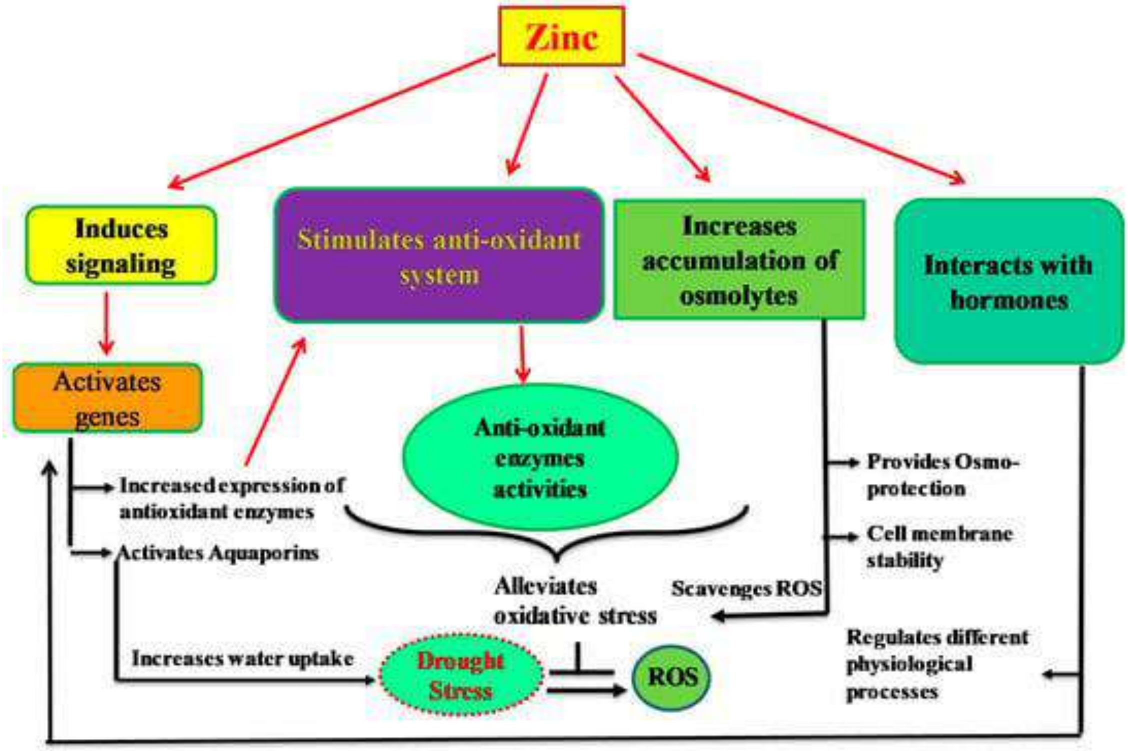


Figure 5. Mechanism of Zn-induced drought stress tolerance (Umair et al., 2020)

Conclusion

The application of zinc has shown promising potential in mitigating the adverse effects of drought stress on wheat plants. Zinc is crucial in maintaining plant physiological and biochemical processes, which are critical under water-limited conditions. Research indicates that Zn application can enhance wheat's drought tolerance by improving antioxidative defense systems, photosynthetic efficiency, osmotic adjustment, and root development. These responses collectively improve water uptake, nutrient assimilation, and overall plant resilience, enhancing growth and grain yield even in challenging environmental conditions. However, the extent of Zn's effectiveness can vary based on factors such as dosage, wheat variety, soil properties, and the severity and timing of drought stress. While Zn application is not a universal solution, it remains a valuable agronomic tool within integrated drought management strategies, especially in Zn-deficient soils where it offers the dual benefit of alleviating Zn deficiency and drought-induced stress.

Future research should explore optimal Zn application rates, methods, and timing specific to drought-prone environments to maximize the beneficial effects on wheat. Additionally, investigating the genetic variation in wheat varieties for Zn uptake and drought tolerance could inform breeding programs to develop drought-resistant, Zn-efficient wheat cultivars. There is also a need for long-term field studies across the diverse agro-climatic region to assess the combined impact of Zn application under real-world drought scenarios, considering soil types, environmental conditions, and other agricultural practices, such as conservation tillage and efficient irrigation systems, could offer more holistic solutions to address both nutrient deficiencies and drought stress in wheat production.

Acknowledgments

The publication is a result of the work on Project KP-06-H 36/15 of 17.12.2019, funded by the Research Fund, Bulgarian Ministry of Education and Science.

References

Ahanger, M.A., MoradTalab, N., Fathi Abd-Allah, E., Ahmad, P., Hajiboland, R., 2016. Plant growth under drought stress: Significance of mineral nutrients. In Water Stress and Crop Plants: A Sustainable Approach; John Wiley & Sons, Ltd.: West Sussex, UK, Volume 2.

Arbona, V., Manzi, M., de Ollas, C., Gómez-Cadenas, A., 2013. Metabolomics as a tool to investigate abiotic stress tolerance in plants. Int. J. Mol. Sci. 14, 4885–4911. https://doi.org/10.3390/ijms14034885

Banerjee, S., Islam, J., Mondal, S., Saha, A., Saha, B., Sen, A., 2023. Proactive attenuation of arsenic-stress by nano-priming: Zinc Oxide nanoparticles in Vigna mungo (L.) Hepper trigger antioxidant defense response and reduce root-shoot arsenic translocation. J Hazard Mater 446,130735. https://doi.org/10.1016/j. jhazmat.2023.130735

Basit, A., Hussain, S., 2024. Arsenic and Zinc Accumulation in Zinc-Biofortified Wheat under Arsenic-Contaminated Irrigation and Varied Zinc Application Methods. Journal of Soil Science and Plant Nutrition 24, 5586–5601. https://doi.org/10.1007/s42729-024-01927-2

Ben, M.S., Soba, D., Zhou, B., Loladze, I., Morales, F., Aranjuelo, I., 2021. Climate change, crop yields, and grain quality of C3 cereals: A meta-analysis of [CO2], temperature, and drought effects. Plants 10, 1052. https://doi.org/10.3390/plants10061052

David, O.A., Osonubi, O., Olaiya, C.O., Agbolade, J.O., Ajiboye, A.A., Komolafe, R.J., Chukwuma, D.M., Akomolafe G.F., 2017. Anatomical Response of Wheat Cultivars to Drought Stress. Ife Journal of Science 19(2), 323 – 331. https://dx.doi.org/10.4314/ijs.v19i2.12

Fatemeh, S., Aghafakhr, M., Ghodratollah, S., Mohammad, R.S., Mehran, S., 2024. Zinc foliar application may alleviate drought stress in wheat species through physiological changes. Plant Stress 13, 100534. https://doi.org/10.1016/j.stress.2024.100534

Khan, H.R., McDonald, G.K., Rengel, Z., 2004. Zinc fertilization and water stress affects plant water relations, stomatal conductance and osmotic adjustment in chickpea (Cicer arientinum L.). Plant Soil 267, 271–284. https://doi.org/10.1007/s11104-005-0120-7

Kheradmand, M.A., Shahmoradzadeh, F.S., Fatahi, E., Raoofi, M.M., 2014. Effect of water stress on oil yield and some characteristics of Brassica napus. Int. Res. J. Appl. Basic Sci. 8, 1447–1453.

Lalarukh, X.W., Amjad, S.F. Hussain, S., Mora-Poblete, F., Abdel-Hafez, S.H., Fawzy, M.A., Abbas, M.H.H., Abdelhafez, A.A. Datta, R., 2022. Chemical role of α-tocopherol in salt stress mitigation by improvement in morpho-physiological attributes of sunflower (Helianthus annuus L.). Saudi J. Biol. Sci. 29, 1386-1393.

Ma, D., Sun, D., Wang, C., Ding, H., Qin, H., Hou, J., 2017. Physiological responses and yield of wheat plants in zinc-mediated alleviation of drought stress. Front. Plant Sci. 8. https://doi.org/10.3389/fpls.2017.00860

Melash, A. A., Ábrahám, É.B., 2022. Barriers and levers to enhance end-use functional properties of durum wheat (Triticum turgidum L.) grain: An agronomic implication. Heliyon 8 (5), e09542. https://doi.org/10.1016/j.heliyon.2022.e09542.

Melash, A.A., Bogale, A.A., Bytyqi, B., Nyandi, M.S., Ábrahám, É.B., 2023. Nutrient management: as a panacea to improve the caryopsis quality and yield potential of durum wheat (Triticum turgidum L.) under the changing climatic conditions. Front. Plant Sci. 14. |https://doi.org/10.3389/fpls.2023.1232675.

Mannan, M.A., Tithi, M.A., Islam, M.R., 2022. Soil and foliar applications of zinc sulfate and iron sulfate alleviate the destructive impacts of drought stress in wheat. CEREAL RESEARCH COMMUNICATIONS 50, 1279–1289. https://doi.org/10.1007/s42976-022-00262-5

Marschner, H., 1995. Mineral nutrition of higher plants. London UK: Academic Press.

Parkash, V., Singh, S., 2020. A review on potential plant-based water stress indicators for vegetable crops. Sustainability 12, 3945. https://doi.org/10.3390/su12103945

Reddy, A.R., Chaitanya, K.V., Vivekanandan, M., 2004. Drought-induced responses of photosynthesis and antioxidant metabolism in higher plants. J. Plant Physiol. , 161, 1189–1202. https://doi.org/10.1016/j.jplph.2004.01.013

Reza, S., 2024. Silicon Improves Bacillus simplex Producing 1-Aminocyclopropane-1- Carboxylic Acid Deaminase Function in Order to Adjust Drought Stress in Wheat. Iranian Journal of Science 48, 1135–1147. https://doi.org/10.1007/s40995-024-01633-9

Sreenivasulu, N., Grimm, B., Wobus, U., Weshke, W., 2000. Differential response of antioxidant compounds to salinity stress in salt-tolerant and salt-sensitive seedlings of foxtail millet (Setaria italica). Physiolgia Plant. 109, 435–442. https://doi.org/10.1034/j.1399-3054.2000.100410.x

Umair, H. M., Aamer, M., Umer Chattha, M., Haiying, T., Shahzad, B., Barbanti, L., Nawaz, M., Rasheed, A., Afzal, A., Liu, Y., Guoqin, H., 2020. The Critical Role of Zinc in Plants Facing Drought Stress. Agriculture 10(9), 396. https://doi.org/10.3390/agriculture10090396

Waraich, E. A., Ahmad, R., Ashraf, M. Y. 2011. Role of mineral nutrition in alleviation of drought stress in plants. Aust. J. Crop Sci. 5, 764.

Xu, D.Q., Huang, J., Guo, S.Q., Yang, X., Bao, Y.M., Tang, H.J., Zhang, H.S., 2008. Overexpression of a TFIIIA-type zinc finger protein gene ZFP252 enhances drought and salt tolerance in rice (Oryza sativa L.). FEBS Lett. 582, 1037–1043.

Yilmaz, A., Ekiz, H., Gültekin, I., Torun, B., Barut, H., Karanlik, S., 1998. Effect of seed zinc content on grain yield and zinc concentration of wheat grown in zinc deficient calcareous soils. J Plant Nutr. 21, 2257–64. https://doi.org/10.1007/978-94-009-0047-9_82

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

Influence of soil properties on groundwater contamination risks to mineral water sources: A review

Farady BANGANA *, Tomasz ZALESKİ
University of Agriculture in Krakow. Department of Soil Science and Soil Protection; Kraków, Poland

***Corresponding Author**

Farady BANGANA
bangana.farady01@gmail.com

Abstract

Mineral water sources, highly valued for their unique composition and health benefits, are significantly affected by geochemical interactions between groundwater and the surrounding soil. Soil properties, including texture, pH, cation exchange capacity, and organic matter content, play a critical role in determining the quality of mineral water by influencing the dissolution and transport of minerals. Additionally, microbial activity in the soil can mediate oxidation-reduction reactions, altering the mobility of both beneficial minerals and potentially harmful contaminants. The interplay of these factors can lead to contamination risks, especially when pollutants are mobilized from the soil into groundwater. This review comprehensively examines the influence of soil properties on groundwater quality, emphasizing the potential contamination risks to mineral water sources. Understanding these interactions is crucial for ensuring the quality and sustainability of mineral water, informing better management practices, and minimizing health risks associated with contamination. Strategies for sustainable management are also discussed to promote the conservation of this valuable natural resource.

Keywords: Groundwater contamination, Microbial activity, Mineral water, Soil properties, Sustainable management

Introduction

Mineral water sources have unique mineral contents and therapeutic properties. The interaction between groundwater and soil plays an important role in defining the mineral content of these water sources, as the water moves through various soil layers, dissolving and transporting minerals from the soil and underlying bedrock. This geochemical process is influenced by several factors, including soil texture, mineral composition, organic matter content, and microbial activity. Comprehending the soil chemistry around mineral water sources is essential for evaluating the quality, sustainability, and health benefits of these waters, which are often used for drinking, spa treatments, and medicinal purposes.

Mineral water is mainly characterized by the presence of dissolved ions such as calcium, magnesium, sodium, potassium, bicarbonates, sulfates, and trace elements like iron, zinc, and manganese. These components are primarily products from the geochemical interactions between infiltrating water and the surrounding soil and rock formations. The type of minerals presents in the soil, as well as the pH, redox conditions, and organic content, significantly affect the solubility and mobility of these ions, determining the specific mineral profile of the groundwater, the behaviour and transport of polluting substances strongly depends on the filtering function of soil (Keesstra et al., 2012). Soil properties such as pH and cation exchange capacity (CEC), play an important role in influencing the solubility and mobility of nutrients and minerals. "The pH of the source of pollution or the polluted soil, is the major factor determining the mobility and/or bioavailability of potentially toxic heavy-metal pollutants" (Nortjé & Laker, 2021). For instance, acidic soils tend to increase the solubility of metals like iron and manganese, enriching the groundwater with these elements. Contrarily, alkaline soils may facilitate the dissolution of calcium and magnesium, contributing to the hardness of the water (McBride, 1994). Additionally, the presence of organic matter in the soil can lead to the formation of complexes with metals, enhancing their mobility into groundwater. The cation exchange capacity of soil, which is the ability of soil particles to exchange cations with the surrounding water, also plays a significant role in determining the concentrations of various dissolved ions in mineral water sources. Moreover, microbial activity in the soil can influence the geochemical processes that govern mineral water composition. Microorganisms can mediate oxidation-reduction reactions, such as the oxidation of sulfides to sulfates or the reduction of iron and manganese oxides, altering the chemical environment and promoting the dissolution of specific minerals into the groundwater (Carter & Gregorich, 2007).

The aim of this review is to explore the various factors influencing groundwater, examining the interactions that affect the mineral content, quality, and sustainability of these unique water bodies. This can better assess the environmental factors impacting mineral water composition and develop strategies for the conservation and sustainable use of these valuable natural resources.

Soil Properties Influencing Mineral Water Composition

Soil Texture and Mineral Composition

Soil texture refers to the relative proportion of particles, sand, silt and clay in a given soil and it affects the water permeability or percolation rate of a soil (Witheetrirong et al., 2011). The soil's texture is a major factor in the infiltration of water into the ground (Folorunso & Aribisala, 2018). It directly affects the movement and the dissolution rates of minerals:

Sandy soils or coarser soils have large pore spaces, this facilitates a rapid water infiltration, allowing minerals and water to percolate quickly but potentially limiting the time for mineral dissolution. In a case of pollution of the soil in an area close to a mineral water source this sandy soils can be an indicator for a need for a thorough analysis of the soil, groundwater and the mineral water in question.

Clay-rich soils, or finer soils with their smaller pore spaces and high surface area, slow down water movement, promoting prolonged contact with soil particles, this lessens the likelihood of soil pollutant reaching the groundwater. For example, in the case of nitrate-nitrogen (NO_3^--N) coarse soils allow it to leach into groundwater faster compared to fine soils (Witheetrirong et al.,2011).

The mineral composition of the soil also plays a significant role as the composition of a soil can provide important information about the parent material on which the soil is formed, material which can directly affect the groundwater. For instance, researches conducted by Siwek and Żelazny, (2019) in the Polish Tatra Mountains to analyse the environmental and anthropogenic factors affecting groundwater, stream water and lake water chemistry have shown that "the total dissolved solids of spring water in the crystalline part of the Tatra Mountains formed of poorly soluble granite and gneiss rocks is many times smaller than that in the sedimentary portion of the Tatra Mountains formed of highly soluble limestones and dolomites." Also Soils rich in carbonate minerals like calcite and dolomite tend to release calcium and magnesium into the groundwater, contributing to its hardness. In contrast, soils with high silica content from quartz or feldspar may contribute fewer ions to the groundwater due to their lower solubility. The major ions in groundwater are mainly derived from various geochemical processes, including the dissolution/precipitation of gypsum, halite, Glauber's salt, feldspars, calcite and dolomite (Fei Liu et al.,2022).

Soil pH and Cation Exchange Capacity (CEC)

Soil pH significantly influences the solubility of minerals, it directly influences sorption/desorption, precipitation/ dissolution, complex formation, and oxidation-reduction reactions (Beata Draszawka-Bołzan, 2017). In acidic soils ($pH < 7$), the solubility of metals like iron, manganese, and aluminum increases, potentially enriching groundwater with these elements. Jenne (1968) stated that hydrous oxides of Fe and Mn play a principal role in the retention of metals in soils. The solubility of Fe and Mn oxides is also pH related. Below pH 6, the oxides of Fe and Mn dissolve, releasing adsorbed metal ions to solution (Esser & El Bassam, 1981). Alkaline soils ($pH > 7$), on the other hand, can enhance the solubility of carbonate minerals, leading to higher concentrations of calcium and bicarbonate in mineral waters. All trace metal hydroxide, oxide, carbonate, and phosphate precipitates form only under alkaline conditions (Lindsay, 1979).

Cation exchange capacity (CEC) measures the soil's ability to retain and exchange positively charged ions (cations) (Carter & Gregorich, 2007). İons like calcium, magnesium, and potassium. Soils with high CEC, typically clay-rich or organic matter-rich soils, can hold onto these cations and gradually release them into the groundwater, influencing its mineral content. Soils with low CEC are more prone to leaching, where nutrients are washed away from the root zone by water movement, leading to nutrient loss and potential groundwater contamination. High CEC soils are better at retaining nutrients, reducing the risk of leaching (Carter & Gregorich, 2007).

Organic Matter Content

The organic matter in the soil contributes to mineral water composition by affecting the solubility and mobility of various ions. When organic material decomposes, it releases humic and fulvic acids, which can form complexes with metals like iron, copper, and zinc, increasing their solubility and mobility into groundwater. For example, although a (pH > 7) generally causes a retention of cationic metals, cationic metal mobility has been observed to increase with increasing pH due to the formation of metal complexes with dissolved organic matter (Beata Draszawka-Bołzan, 2017). The presence of organic acids can also enhance the weathering of minerals, further enriching the groundwater with dissolved ions.

Microbial Influence on Soil and Mineral Water Chemistry

Microbial activity is a critical factor in shaping the chemical profile of mineral water sources. Soil microorganisms mediate a variety of geochemical processes that influence the concentration of specific ions in groundwater. Microbes can influence the redox potential of the soil, affecting the solubility of redox-sensitive elements like iron, manganese, and sulfur (Carter & Gregorich, 2007). For example, Sulfate-reducing bacteria can convert sulfate (SO_4^{2-}) to sulfide (S^{2-}), affecting the sulfate levels in mineral waters. This process is common in anaerobic conditions where organic matter is abundant. Iron and manganese-oxidizing bacteria play a role in the redox reactions of these metals. In oxygen-poor environments, microbes can reduce insoluble ferric (Fe^{3+}) and manganic (Mn^{4+}) oxides to soluble ferrous (Fe^{2+}) and manganous (Mn^{2+}) forms, respectively, increasing their concentrations in mineral water.

Human Impact on Soil Chemistry Around Mineral Water Sources

Agricultural Activities

Groundwater quality can be strongly affected by many land management techniques. Under agricultural production, the application of agrochemicals can lead to an accumulation of fertiliser residue and pesticides, as well as their metabolites and accompanying heavy metals, in soil, sediment and water (Keesstra et al., 2012). Agriculture can significantly alter the soil chemistry around mineral water sources. The use of fertilizers and pesticides introduces nitrates, phosphates, and various chemicals into the soil, which may leach into groundwater, impacting its quality (Payraudeau, Gregoire 2011). “Many studies indicate that nitrogen from synthetic fertilizers is the most important nitrate source in groundwater contamination” (Bouchard et al., 1992).

Apart from active addition of potentially polluting substances, tillage can also lead to severe groundwater pollution problems. Tillage under forest cover can cause a major increase in humus mineralisation leading to nitrate and nitrite formation and desorption of heavy metals with subsequent leaching to the groundwater (Geissen et al.2003).

Industrial Pollution

Industrial activities close to mineral water sources can introduce heavy metals (e.g., lead, cadmium, and arsenic) and organic pollutants (e.g., petroleum products) into the soil. These contaminants can be mobilized into groundwater through leaching and percolation, altering the mineral composition and potentially posing health risks.

A study by Peiyue Li et al., (2013) in an industrial park, northwest China showed that the groundwater in the studied area has been contaminated conjunctively by natural processes and industrial and agricultural activities; while other contaminants were mainly originated from mineral weathering and water–rock interactions, nitrate and heavy metals such as Mn were mainly affected by human agricultural activities and industrial production.

Urbanization

Urbanization impacts soil and groundwater chemistry by increasing impermeable surfaces, reducing natural infiltration, and altering the hydrological balance. “Many intense human activities such as urbanization, industrialization, mining activities, and agricultural intensification have impacted regional groundwater quality in recent decades on a global scale” (Yong Qian et al., 2023). For example, Gan et al., (2022) reported that domestic sewage and animal waste were the main sources of groundwater nitrate pollution in several alluvial-pluvial fans in the Hebei Plain (China) due to urbanization and agricultural activities. Stormwater runoff from urban areas can carry pollutants into the soil, where they may leach into groundwater, affecting its mineral and chemical profile.

Case Studies

• A study conducted by Jasik & Małek, (2013) in the Łysogóry Mts. in Świętokrzyski National Park in Poland, where spring water samples were collected and analysed, confirmed that spring water quality strongly depended on wet acid deposition and the geological structure.

• A study by Zhang et al., (2024) on the confined groundwater of arid sedimentary plains showed a higher than the prescribed standard of fluoride(F^-) which was mainly due to geological factors such as mineral dissolution, cation exchange, and competitive adsorption of HCO_3^- and possibly from groundwater extraction.

• In the Southern Plain of Hebei Province, China where a study conducted by Longqiang Zhang et al., (2023) it was found that The hydrochemical composition was dominated by water–rock interactions of natural processes, including silicate weathering, dissolution of sulfate minerals (gypsum, anhydrite), and cation-exchange adsorption and also that Anthropogenic activities were the main factor causing NO_3^- content in some groundwater samples to exceed the geochemical baseline.

• A study by Liu et al., (2023) explored the factors influencing groundwater fluoride levels in coastal areas of Hainan Island (South China). It identified soil properties, particularly the mineral composition of the vadose zone, as key factors. Fluoride contamination was primarily due to the leaching of fluorine-containing minerals in soils, exacerbated by agricultural practices and irrigation. This study provides insights into the role of soil mineralogy and human impacts on the chemical composition of groundwater

Conclusion

The soil around mineral water sources play an important role in the composition of these waters. The soil's properties such as its texture, pH, CEC, and organic matter content, along with microbial activity, significantly influence the dissolution and mobility of minerals into groundwater. These influences should not be ignored for a sustainable use of mineral waters not forgetting that human activities too, including agriculture, industrial pollution, and urbanization, can further alter soil chemistry, impacting the quality and sustainability of mineral water sources. Future research should focus on: Understanding the long-term impacts of climate change on soil chemistry and its influence on mineral water quality. Developing sustainable land use practices to protect the natural chemistry of soils around mineral water sources. Utilizing advanced geochemical modelling and monitoring techniques to better predict changes in mineral water composition and guide conservation efforts. By addressing these research gaps, we can improve the management of mineral water sources, ensuring their continued availability and quality for future generations.

Acknowledgments

The publication is a result of the work on Project KP-06-H 36/15 of 17.12.2019, funded by the Research Fund, Bulgarian Ministry of Education and Science.

References

Nortjé, G.P., Michiel, C.L., 2021. Factors that determine the sorption of mineral elements in soils and their impact on soil and water pollution. Minerals, 11(8), 821. doi:https://doi.org/10.3390/min11080821

Jasik, M., Małek, S., 2013. Quality assessment of spring water from the area of the Łysogóry Mts. in Swiętokrzyski National Park in 2010. Folia Forestalia Polonica, 55(1), 27-32

Keesstra, S.D., Geissen, V., Mosse, K., Piiranen, S., Scudiero, E., Leistra, M., van Schaik, L., 2012. Soil as a filter for groundwater quality. Current Opinion in Environmental Sustainability, 4(5), 507-516.

Payraudeau, S., Gregoire, C., 2012. Modelling pesticides transfer to surface water at the catchment scale: a multi-criteria analysis. Agron. Sustain. Dev. 32, 479–500 (2012). https://doi.org/10.1007/s13593-011-0023-3

Geissen, V., Kim, R.Y., Schöning, A., Schütte, S., Brümmer, G.W., 2003. Effects of strip wise tillage in combination with liming on chemical and physical properties of acidic spruce forest soils after clear cutting. Forest ecology and management, 180(1-3), 75-83.

Folorunso, O., Aribisala, J., 2018. Effect of soil texture on soil infiltration rate. Archives of Current Research International, 14(3), 1-8.

Witheetrirong, Y., Tripathi, N.K., Tipdecho, T., Parkpian, P., 2011. Estimation of the effect of soil texture on nitrate-nitrogen content in groundwater using optical remote sensing. International journal of environmental research and public health, 8(8), 3416–3436. https://doi.org/10.3390/ijerph8083416

Zhang, Y., Xiao, Y., Yang, H., Wang, L., Wang, J., Hu, W., Guo, X., 2024. Hydrogeochemical features, genesis, and quality appraisal of confined groundwater in a typical large sedimentary plain. Water Environment Research, 96(8), e11088.

Siwek, J., Żelazny, M., 2019. Environmental and anthropogenic factors affecting water chemistry in the Polish Tatra Mountains.

Zhang, L., Dong, D., Lv, S., Zhang, J., Yan, M., Han, G., Li, H., 2023. Hydrochemical Characterization and Quality Assessment of Groundwater in the Southern Plain of Hebei Province, China. Water, 15(21), 3791.

Qian, Y., Hou, Q., Wang, C., Zhen, S., Yue, C., Cui, X., Guo, C., 2023. Hydrogeochemical Characteristics and Groundwater Quality in Phreatic and Confined Aquifers of the Hebei Plain, China. Water, 15(17), 3071.

Gan, L., Huang, G., Pei, L., Gan, Y., Liu, C., Yang, M., Song, J., 2022. Distributions, origins, and health-risk assessment of nitrate in groundwater in typical alluvial-pluvial fans, North China Plain. Environmental science and pollution research, 1-18.

Liu, F., Zou, J., Liu, J., Zhang, J., Zhen, P., 2022. Factors controlling groundwater chemical evolution with the impact of reduced exploitation. Catena, 214, 106261.

Liu, R., Li, X., Yang, X., Zhang, M., 2023. Occurrence of and Factors Affecting Groundwater Fluoride in the Western Coastal Area of Hainan Island, South China. Water, 15(20), 3678.

Li, P., Wu, J., Qian, H., Lyu, X., Liu, H., 2014. Origin and assessment of groundwater pollution and associated health risk: a case study in an industrial park, northwest China. Environmental geochemistry and health, 36, 693-712.

Lindsay, W.L., 1981. Chemical equilibria in soils (p. 449pp).

Jenne, E.A., 1968. Controls on Mn, Fe, Co, Ni, Cu, and Zn concentrations in soils and water: the significant role of hydrous Mn and Fe oxides.

Esser, J., El Bassam, N., 1981. On the mobility of cadmium under aerobic soil conditions. Environmental Pollution Series A, Ecological and Biological, 26(1), 15-31.

Draszawka-Bolzan, B., 2017. Effect of pH and soil environment. World News of Natural Sciences, 8.

Carter, M. R., Gregorich, E.G., 2007. Soil sampling and methods of analysis. CRC press.

Bouchard, D.C., Williams, M.K., Surampalli, R.Y., 1992. Nitrate contamination of groundwater: sources and potential health effects. Journal-American Water Works Association, 84(9), 85-90.

McBride, M.B., 1994. Environnmental chemistry of Soil.

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

Comprehensive review on heavy metal pollution in urban soils: Sources, risk assessment, and impacts

Hassan Esmaeili GISAVANDANI *, Michał GĄSIOREK
University of Agriculture in Krakow. Department of Soil Science and Soil Protection; Kraków, Poland

***Corresponding Author**

Hassan ESMAEILI GISAVANDANI
esmaeili.gisavandani@gmail.com

Abstract

Heavy metal contamination in urban soils has emerged as a pressing environmental challenge, carrying significant implications for public health, ecological integrity, and sustainable urban development. This review synthesizes findings from key studies to examine the concentrations, sources, and risks associated with heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), zinc (Zn), and mercury (Hg) in urban soils across diverse geographic regions. Key pollution sources include industrial emissions, vehicular exhaust, construction activities, mining, and the excessive use of fertilizers and pesticides. Elevated metal concentrations in urban parks, industrial zones, and areas with high urbanization levels are linked to soil toxicity, biodiversity loss, and reduced ecosystem services. Risk assessments reveal severe health implications, particularly for vulnerable groups such as children, who are at greater risk of exposure through direct soil contact or ingestion of contaminated food and water. Health impacts include neurological damage, kidney disorders, developmental delays, and an increased risk of cancers. Additionally, contaminated soils impact urban vegetation and wildlife, disrupting local ecosystems and compromising urban green spaces. This review highlights the urgent need for integrated mitigation strategies, including stricter regulatory measures, advanced soil monitoring systems, sustainable remediation technologies, and community awareness programs. By implementing such measures, it is possible to reduce pollution levels, protect public health, and ensure sustainable urban growth while preserving environmental quality. The findings underscore the importance of a multidisciplinary approach to address the complex challenges posed by heavy metal contamination in urban soils. Key words: Heavy Metal Pollution, Urban soils, Ecological risks, Soil remediation, soil contamination.

Keywords: Heavy metal pollution, Urban soils, Health risks, Pollution sources

Introduction

Soil, a fundamental element of urban life, undergoes change influenced by both natural processes and human actions (Gąsiorek et al., 2017; Liu et al., 2020). Urbanization transforms the soil, making it distinct from its natural state and inadvertently accumulating heavy metals (Chen et al., 2005).

Heavy metal contamination in urban soils is an emerging global concern due to its adverse effects on human health, soil quality, and the broader environment. In urbanized areas, industrialization, vehicular emissions, and urban development contribute significantly to the accumulation of hazardous elements in soils. This review synthesizes findings from five studies that examine heavy metal concentrations, their sources, and associated risks in urban parks and industrial areas from diverse regions, including China, Poland, and Nigeria. The studies explore various assessment methods, sources of pollution, and the implications for human health.

Heavy Metal Pollution in the Planty Park, Krakow, Poland (Gąsiorek et al., 2017)

In Krakow's Planty Park, Poland, field studies conducted in June 2014 involved collecting representative soil samples (0–20 cm) from 50 random points (Fig. 1). Soil properties, including texture, pH, Total Organic Carbon (TOC), and Total Nitrogen (Nt), were determined, and heavy metal content was analyzed using Atomic emission spectrometry with inductively coupled plasma (ICP-OES). Pollution indices were calculated based on established formulas (Gąsiorek et al., 2017).

Gąsiorek et al. (2017) assessed heavy metal pollution in the topsoil of the historical Planty Park in Krakow, Poland. Historical chapters, marked by medieval ore processing and industrial revolutions, imprint Krakow's Planty Park with the echoes of the city's evolution (Gąsiorek et al., 2017; Kowalska et al., 2016). The study revealed that the highest concentrations of lead (Pb), cadmium (Cd), and zinc (Zn) were located near major roads and areas with high pedestrian traffic. The primary sources of contamination were identified as traffic emissions, construction activities, and historical industrial operations. The researchers conducted a comprehensive assessment using pollution indices such as the contamination factor (CF) and pollution load index (PLI), which confirmed significant soil pollution in these areas. The results also indicated the potential ecological risks to park vegetation and wildlife, as well as the need for long-term monitoring and remedial measures.

Pollution Sources and Health Risks in Northwest China (Li et al., 2022)

Li et al. (2022) focused on the soil contamination levels of heavy metals in northwest China, particularly in areas affected by rapid industrialization and urbanization. Their research indicated high concentrations of lead (Pb), cadmium (Cd), and mercury (Hg) in urban soils, linked to industrial emissions, mining, and the use of contaminated water for irrigation. Risk assessments highlighted that soil contamination poses significant health risks to the population, particularly in heavily industrialized regions. The study emphasized the need for more stringent environmental regulations and effective soil remediation strategies to address the contamination levels and reduce the associated health risks.

Heavy Metal Pollution in Urban Parks of Beijing, China (Liu et al., 2020)

In the research of Liu et al. (2020), 121 parks (Fig. 2) were studied in Beijing. Topsoil samples (0–5 cm) underwent inductively coupled plasma-mass spectrometry (ICPMS) analysis for heavy metal(loid)s, and a conditional inference tree model was used to establish relationships between variables. Liu et al. (2020) investigated the concentrations of heavy metals in the topsoil of urban parks in Beijing, China. The study found elevated levels of several heavy metals, including cadmium (Cd), lead (Pb), and arsenic (As), particularly near busy traffic areas and industrial zones. The primary sources of contamination were identified as vehicular emissions, industrial activities, and construction dust. The researchers performed risk assessments based on the concentration of metals and found that human health risks, especially for children who frequently play in these parks, were significant due to the bioavailability of these metals. The study underscores the need for regular monitoring of urban park soils and the implementation of pollution control measures to mitigate risks.

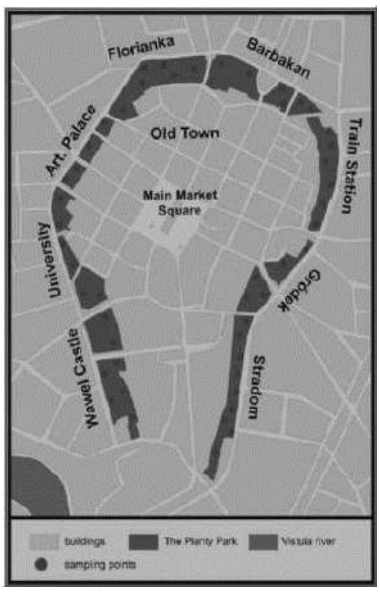


Figure 1: Location of study area. Urban parks Planty Park, Krakow (Gąsiorek et al., 2017)

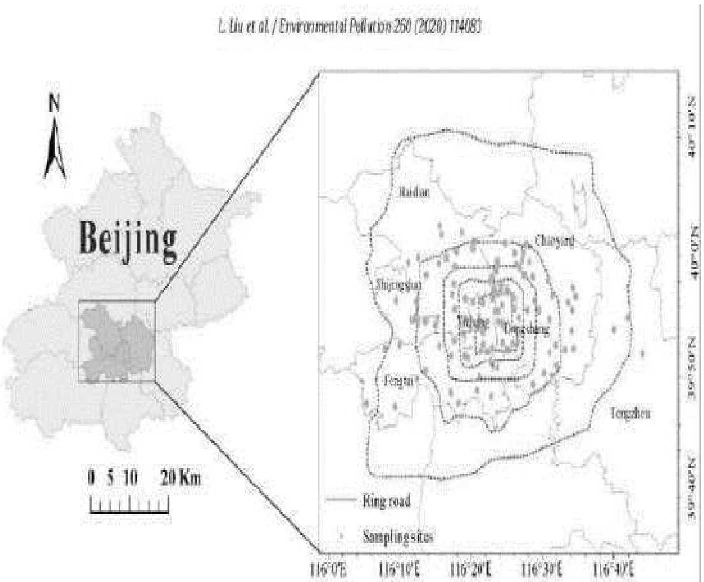


Figure 2. Sampling sites of soils taken from Beijing (Liu et al., 2020)

Heavy Metal Levels in Lagos, Nigeria (Anyakora et al., 2013)

Anyakora et al. (2013) investigated heavy metal levels in soil samples from highly industrialized areas of Lagos, Nigeria. The study identified elevated concentrations of lead (Pb), cadmium (Cd), and nickel (Ni) in urban soils, which were attributed to industrial emissions, improper waste disposal, and vehicular emissions. The study also explored the potential for soil contamination to spread to surrounding environments, including water bodies. The findings highlighted the health risks posed by high levels of these metals, particularly the neurological and renal effects of lead exposure. The study recommended more rigorous environmental monitoring and public health interventions to mitigate the impact of soil contamination.

Variation in Pollution Status in Urbanized Regions (Zheng et al., 2023)

Zheng et al. (2023) analyzed the variation in heavy metal pollution levels in soils from urban regions with different levels of urbanization across China. The study found that areas with higher urbanization and industrialization exhibited significantly higher concentrations of metals such as cadmium (Cd), copper (Cu), and zinc (Zn) (Fig 3). Pollution sources were identified as industrial emissions, urban construction, and traffic. The research emphasized that urbanization exacerbates heavy metal pollution and increases the associated health risks, particularly in densely populated areas. The study also proposed risk assessments and suggested that policymakers prioritize pollution control strategies based on the levels of urbanization.

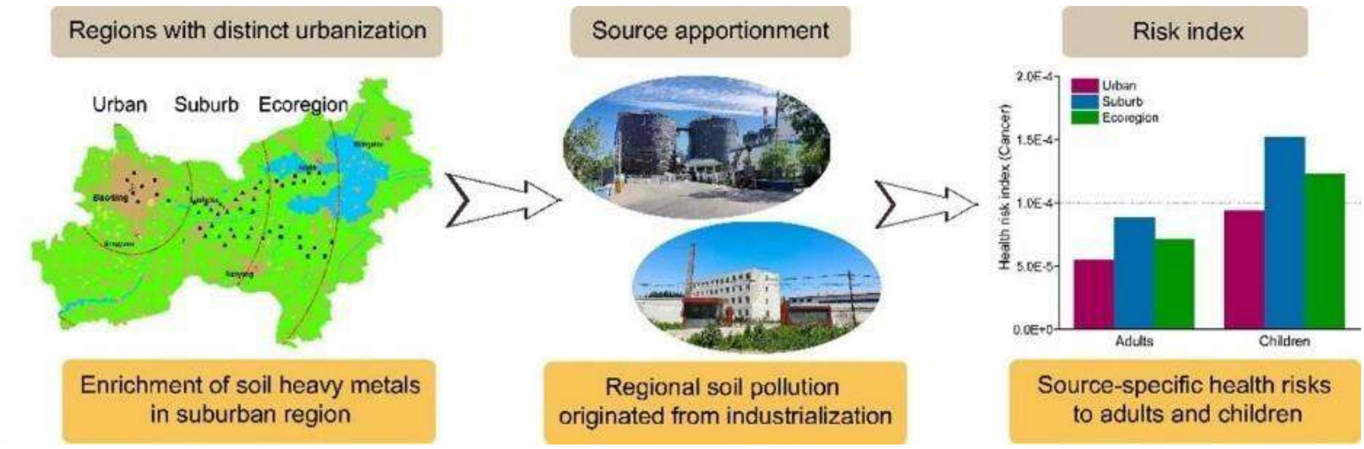


Figure 3. Urbanization assocated soil pollution (Zheng et al., 2023)

Table 1. Comparative analysis of the studies

Study	Region	Main Sources of Pollution	Key Findings	Methodology
Gąsiorek et al. (2017)	Krakow, Poland	Traffic emissions, historical industrial activities, construction	High Pb, Cd, and Zn in topsoil; ecological risks to park vegetation	Soil sample analysis, contamination indices (CF, PLI)
Li et al. (2022)	Northwest China	Industrial emissions, mining, irrigation with contaminated water	High Pb, Cd, and Hg levels; significant human health risks	Soil sample analysis, risk assessment
Liu et al. (2020)	Beijing, China	Traffic emissions, industrial activities, construction dust	Elevated levels of Cd, Pb, and As; health risks for children	Soil sample analysis, risk assessment
Anyakora et al. (2013)	Lagos, Nigeria	Industrial emissions, waste disposal, vehicular emissions	Elevated Pb, Cd, and Ni levels; significant health risks	Soil sample analysis, pollution source identification
Zheng et al. (2023)	China	Industrial emissions, urban construction, traffic	High Cd, Cu, and Zn levels; risk assessment in urbanized areas	Soil sample analysis, risk assessment

Results And Discussion

The studies reviewed highlight the widespread contamination of urban soils with heavy metals, with concentrations varying based on geographical location, industrial activities, traffic emissions, and agricultural practices. In many urban areas, such as Beijing, China, and Lagos, Nigeria, elevated levels of metals like lead (Pb), cadmium (Cd), and zinc (Zn) were found, often exceeding recommended safety limits (Liu et al., 2020; Anyakora et al., 2013). In Beijing, for example, topsoil in urban parks showed significant contamination, primarily from traffic-related emissions, with lead concentrations found to be well above background levels (Liu et al., 2020).

A comparative analysis across various regions, including Europe, Asia, and Africa, revealed that traffic emissions and industrial discharge were the dominant sources of contamination in urban parks, particularly in cities with high levels of vehicular traffic and industrial activities (Wawer et al., 2015; Zheng et al., 2023). In addition, agricultural practices contributed to the contamination of soils in areas near farmland, especially where intensive use of fertilizers and pesticides was common (Li et al., 2022).

Risk assessments from these studies indicated that the concentrations of heavy metals in urban soils pose significant ecological and human health risks. Elevated levels of metals like cadmium and lead were linked to neurological damage in children, kidney disorders, and even cancer in areas with prolonged exposure (Li et al., 2022). The impact of these pollutants extends to soil fertility, with metals such as cadmium causing toxicity to plants, reducing biodiversity, and impairing the growth of essential crops (Gąsiorek et al., 2017).

In addition, studies also pointed out that urban parks, often located near traffic corridors, are hotspots for contamination. The contamination levels in these areas were particularly concerning because they are frequently accessed by the public, raising the risk of exposure to harmful pollutants (Wawer et al., 2015).

The studies examined in this review highlight the pervasive and growing issue of heavy metal contamination in urban soils worldwide. The sources of pollution are multifaceted, with traffic emissions, industrial activities, and construction operations being the most commonly cited contributors across different regions. For instance, Liu et al. (2020) and Zheng et al. (2023) found that urban areas with dense traffic and industrial zones, such as Beijing and northwest China, had high concentrations of heavy metals like cadmium (Cd), lead (Pb), and arsenic (As). These pollutants primarily emanate from vehicular exhaust, industrial discharges, and soil disturbances related to construction. The findings from Gąsiorek et al. (2017) and Anyakora et al. (2013) further corroborate this, identifying traffic and historical industrial activities as major sources in Krakow, Poland, and Lagos, Nigeria, respectively.

The risk posed by heavy metals is particularly concerning in urban parks and other public spaces, where people, especially children, are more likely to come into direct contact with contaminated soil. Liu et al. (2020) emphasized the heightened risk in urban parks of Beijing, where concentrations of metals like Pb and As were linked to adverse health effects, including neurotoxic effects in children. Similarly, the studies by Li et al. (2022) and Zheng et al. (2023) show that industrialization and urbanization significantly contribute to human health risks. For instance, Li et al. (2022) highlighted how contamination from industrial sources, compounded by water pollution, raised the risks of heavy metal exposure in northwest China. Chronic exposure to these metals has been shown to cause a variety of illnesses, such as kidney failure, neurological damage, and even cancers (Yang et al., 2018).

Ecological risks are also significant, particularly in areas where vegetation may absorb contaminated soil. Gąsiorek et al. (2017) found that heavy metal pollution in the Planty Park of Krakow posed risks not only to human health but also to plant and animal species within the park. This observation underscores the broader environmental impact, where pollution not only affects human populations but disrupts local ecosystems. For example, high concentrations of cadmium (Cd) and zinc (Zn) were found to reduce plant growth and biodiversity in urban parks, thus affecting ecosystem stability.

Moreover, studies such as those by Li et al. (2022) and Zheng et al. (2023) emphasize the importance of regional differences in pollution sources. While industrialization and mining are major contributors in China and other industrialized countries, waste disposal and vehicular emissions are more significant in rapidly urbanizing regions like Nigeria and Poland. This highlights the need for localized pollution control measures tailored to specific sources, which can vary dramatically depending on the level of urbanization and industrialization in a given area.

Conclusion

The findings from these studies highlight the urgent need for comprehensive soil monitoring and risk assessment in urban areas to manage heavy metal pollution effectively. Strategies for pollution control, including stricter industrial regulations, improved waste management practices, and increased public awareness, are essential to mitigating the impact of heavy metals on human health and the environment. Moreover, the use of contamination indices and risk assessment models provides valuable tools for understanding the extent of soil pollution and guiding remediation efforts. Continued research into urban soil pollution and its long-term effects on ecosystems and public health is essential for developing sustainable urban planning and environmental policies.

References

Anyakora, C., Ehianeta, T., Umukoro, O., 2013. Heavy metal levels in soil samples from highly industrialized Lagos environment. African Journal of Environmental Science and Technology, 7(9), pp.917-924.

Chen, T.B., Zheng, Y.M., Lei, M., Huang, Z.C., Wu, H.T., Chen, H., Fan, K.K., Yu, K., Wu, X., Tian, Q.Z., 2005. Assessment of heavy metal pollution in surface soils of urban parks in Beijing, China. Chemosphere, 60(4), pp.542-551.

Gąsiorek, M., Kowalska, J., Mazurek, R., Pająk, M., 2017. Comprehensive assessment of heavy metal pollution in topsoil of historical urban park on an example of the Planty Park in Krakow (Poland). Chemosphere, 179, pp.148-158.

Kowalska, J., Mazurek, R., Gąsiorek, M., Setlak, M., Zaleski, T., Waroszewski, J., 2016. Soil pollution indices conditioned by medieval metallurgical activity–A case study from Krakow (Poland). Environmental Pollution, 218, pp.1023-1036.

Liu, L., Liu, Q., Ma, J., Wu, H., Qu, Y., Gong, Y., Yang, S., An, Y., Zhou, Y., 2020. Heavy metal (loid) s in the topsoil of urban parks in Beijing, China: Concentrations, potential sources, and risk assessment. Environmental Pollution, 260, p.114083.

Li, F.J., Yang, H.W., Ayyamperumal, R., Liu, Y., 2022. Pollution, sources, and human health risk assessment of heavy metals in urban areas around industrialization and urbanization-Northwest China. Chemosphere, 308, p.136396.

Wawer, M., Magiera, T., Ojha, G., Appel, E., Kusza, G., Hu, S., Basavaiah, N., 2015. Traffic-related pollutants in roadside soils of different countries in Europe and Asia. Water, Air, & Soil Pollution, 226, pp.1-14.

Zheng, F., Guo, X., Tang, M., Zhu, D., Wang, H., Yang, X., Chen, B., 2023. Variation in pollution status, sources, and risks of soil heavy metals in regions with different levels of urbanization. Science of The Total Environment, 866, p.161355.

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

Effect of some soil characteristics on plant minerals uptake and plant growth

Kamiran Azeez Mahmood GRAVI [a], Haya ABU SALIH [b,*], Ayhan HORUZ [b]

[a] University of Duhok, College of Agricultural Engineering Sciences, Department of Soil and Water Sciences, Iraq
[b] Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Haya ABU SALIH
abusalihhaya@gmail.com

Abstract

This review brings together recent research on the impact of specific soil properties on plant mineral uptake and plant growth. Soil properties significantly affect plant nutrient uptake and growth, shaping agricultural productivity and ecosystem health. Soil texture affects water retention, drainage, and nutrient availability. Clay soils, with high cation exchange capacity. Conversely, sandy soils facilitate root growth but often require more frequent fertilization. Soil organic matter enhances nutrient availability with humus playing a critical role in maintaining soil fertility. Soil pH affects nutrient solubility and microbial activity. Nutrient uptake and root development can be impaired if the pH is at extreme levels. Soil moisture is critical for dissolving. However, excess moisture can reduce soil aeration, by preventing root respiration. Soil salinity, characterized by high concentrations of soluble salts, creates osmotic stress, reducing water and nutrient uptake. Understanding these soil properties and their interactions with plant physiology are essential to optimize soil management practices.

Keywords: Nutrient uptake, Plant growth, Root system, Soil properties

Introduction

The rhizosphere is the narrow region of soil surrounding plant roots, influenced by chemicals released from the roots. Defined by Hiltner in 1904, it hosts unique microorganisms and varies in shape and size depending on plant root characteristics. It constitutes only 2-3% of total soil volume (Coleman et al., 1977) but plays a key role in ecosystem functions.

The rhizosphere is divided into two zones based on proximity to the root (Figure 1):

1. Endorizosphere: Refers to the inner root zone colonized by microbes that utilize organic compounds secreted by the root. This term was introduced in 1978 (Balandreau & Knowles) and further elaborated by Burns and Slater (1982), Klepper (1992), and Walker et al. (2003).

2. Ectorizosphere: Comprises the soil particles surrounding the root. While some studies consider it part of the soil, not the root, its influence on root-soil interactions is significant (Bashir et al., 2016; Brundrett, 2009; Lambers et al., 2008).

These zones are crucial for plant growth and nutrient uptake, supporting biogeophysical processes essential to the ecosystem.

Effect of Soil Texture on Plant Growth

Soil texture refers to the proportions of sand, silt, and clay particles in soil, influencing its physical and chemical properties and plant development.

1. Clay Soils: Soils with the smallest particle size, less than 0.002 mm, exhibit a large surface area and a high cation exchange capacity (CEC), which allows them to retain essential nutrients such as calcium, magnesium, potassium, and ammonium (Roy et al., 2006). This characteristic enhances nutrient retention and availability, benefiting plant growth. However, their high compaction potential can restrict root growth and limit access to nutrients deeper in the soil profile. Proper management practices are crucial to mitigate these challenges and

optimize soil performance (Jones & Jacobsen, 2005). The combination of a high surface area and net surface charges makes these soils particularly effective in nutrient retention.

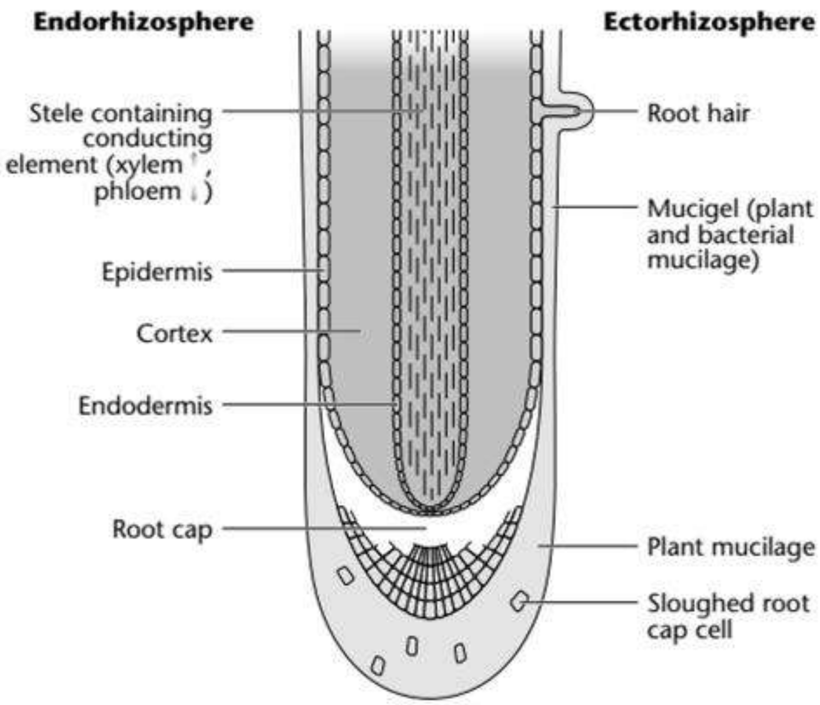


Figure 1: The rhizosphere zones (J. M. Lynch et al., 2001)

2. Sandy Soils: Soils with the largest particle size, ranging from 2.0 to 0.05 mm, have a coarse texture and low cation exchange capacity (CEC), which limits their ability to hold nutrients and increases the risk of nutrient leaching due to rapid drainage (Jones & Jacobsen, 2005). While their structure facilitates easier root growth, these soils often struggle to retain adequate water and nutrients in the root zone, posing challenges for plant development (Yu et al., 2024).

3. Silt Soils: Soils with intermediate particle sizes, ranging from 0.05 to 0.002 mm, strike a balance between nutrient and water retention and drainage. They retain more nutrients and water compared to coarse-textured sandy soils while still allowing for adequate drainage, making them suitable for supporting healthy plant growth.

4. Loamy Soils: Soils with a balanced mix of sand, silt, and clay, known as loam, combine the benefits of each particle type. This structure provides optimal water retention, drainage, aeration, and nutrient-holding capacity, making it ideal for supporting most plants. Loam soils are highly versatile and promote healthy plant growth by maintaining a favorable balance of moisture and nutrients.

Understanding soil texture is essential for proper soil management to support healthy plant development. These variations in soil texture determine its suitability for different plants and agricultural practices.

Soil Structure and Its Impact on Plant Growth

Soil structure refers to the arrangement and aggregation of soil particles into various forms, described by type (shape and arrangement), class (size), and grade (degree of aggregation) (Arunkumar, 2021). It significantly influences soil health by affecting properties such as permeability, water retention, aeration, and nutrient availability.

1. Role in Plant Growth: Soil structure determines water and air movement, nutrient availability, and root penetration. Poorly structured, compacted, or dry soils hinder plant root growth and nutrient uptake (Schroth & Sinclair, 2003). Well-structured soils provide suitable pathways for root growth, water infiltration, and biochemical exchanges, supporting diverse life forms and enhancing plant health (J. P. Lynch et al., 2021).

2. Formation of Soil Structure: Soil aggregates are held together by forces from clay particles, organic matter, and cementing processes. Roots influence soil structure by creating pores for water and air and exuding compounds that attract beneficial microbes, enhancing aggregation (Pierret et al., 2005). Roots stabilize the soil, reduce erosion and contribute to carbon storage and nutrient cycling.

Understanding the relationship between soil structure and plant roots is vital for promoting sustainable agriculture and enhancing plant productivity. Managing soil to maintain good structure ensures better root development, water retention, and nutrient availability, ultimately supporting plant health.

Effect of Soil Organic Matter on Soil Properties and Plant Growth

Soil comprises 50% of solids (primarily minerals and organic matter), 25% liquid, and 25% gases (NRCS). While organic matter constitutes a smaller fraction by weight compared to minerals, it has significant effects on soil properties and plant growth. The Food and Agriculture Organization (FAO) defines soil organic matter as all organic materials in the soil, classified into three groups: humus (fully decomposed, stable matter), soil organism biomass, and partially decomposed residues. Organic matter consists of elements like carbon, oxygen, hydrogen, nitrogen, phosphorus, and sulfur, which contribute to plant nutrient needs. Its decomposition releases amino acids and carbon dioxide, enhancing the plant's ability to absorb elements like calcium, magnesium, and potassium.

Organic matter improves soil structure, facilitating water and air movement necessary for plant roots. Additionally, higher organic matter content darkens soil color, aiding heat absorption and stimulating biological processes essential for soil aeration and microbial activity. This improved soil environment promotes plant growth. Research by Hudson (1994) found that every 1% increase in organic matter raises soil water-holding capacity by 3.7%.

A notable example of organic matter is the humus, which forms from decomposed plant and animal residues in anaerobic conditions. Containing 60% carbon, 6% nitrogen, and smaller amounts of phosphorus and sulfur, humus decomposes slowly and can remain in soil for centuries. It enhances nutrient and water retention, acting as a chelator to make nutrients more available to plants. A study by Grossl and Inskeep (1991) demonstrated that humus prevents calcium phosphate precipitation and prolongs phosphate fertilizer solubility.

Overall, organic matter, including humus, directly improves soil structure, water retention, nutrient availability, and biological activity, benefiting plant health and productivity (Andreux, 1996; Chaney & Swift, 1984; Konen et al., 2003; Kumar et al., 2020; McCauley et al., 2009; Rajendra Prasad & Power, 1997).

Effects of Soil pH on Plant Growth and Soil Properties

Soil pH significantly affects nutrient availability, microbial activity, and plant root development. Most plants thrive in a slightly acidic to neutral pH range (6.0–7.0), where nutrient availability is optimal. In acidic soils, toxic elements like aluminum and manganese can accumulate, while in alkaline soils, nutrients such as iron, phosphorus, and manganese become less accessible to plants (Arduini et al., 1998).

Microbial diversity and activity are also influenced by soil pH, as microorganisms involved in nutrient cycling, organic matter decomposition, and disease suppression require specific pH conditions. Changes in pH can alter microbial populations, impacting nutrient availability and soil structure (Pietri & Brookes, 2008; Wei et al., 2024).

Soil pH directly affects root growth and elongation. Extreme pH levels can damage root tissues and limit root penetration, reducing the plant's ability to absorb water and nutrients effectively (Walter et al., 2000). Additionally, soil pH influences the solubility of nutrients and the effectiveness of fertilizers, which are often pH dependent. Adjusting soil pH to optimal levels can enhance nutrient supply and microbial processes, promoting healthy plant growth. For instance, higher pH improves the availability of micronutrients that support plant development (Gondal et al., 2021). Thus, maintaining an appropriate soil pH is crucial for supporting plant health by ensuring balanced nutrient availability, robust root development, and a thriving soil microbial ecosystem.

Effect of Soil Humidity on Plant Growth

Soil humidity, or soil moisture, is a critical factor for plant growth, serving as the primary water source absorbed by roots for vital processes like photosynthesis and transpiration. Water in the soil dissolves nutrients, making them available for root uptake, and supports seed germination by activating specific enzymes. However, an excess of soil moisture reduces oxygen levels in soil pores, inhibiting root respiration and potentially causing plant death (Veihmeyer & Hendrickson, 1927).

Water deficits impact various physiological processes. Cell expansion can tolerate water stress up to -10 bar, while protein and cell wall synthesis endure slightly more. Photosynthesis and stomatal conductance are affected at water deficits up to -20 bar, prompting the plant to release abscisic acid, which closes stomata to reduce water loss and manage stress (Allison & Jones, 2005).

Thus, maintaining optimal soil moisture is essential to balance oxygen availability and support the physiological needs of plants.

Effect of Soil Salinity on Plant Growth

Soil salinity refers to the concentration of soluble salts, primarily ions like sodium (Na^+), chloride (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), and sulfate (SO_4^{2-}), present in the soil. It is commonly measured as electrical conductivity (EC) in decisiemens per meter (dS/m) or as total dissolved salts (TDS) in milligrams per liter (mg/L) (Butcher et al., 2016; El-Ghazlane et al., 2017). High soil salinity, indicated by EC values exceeding 4 dS/m, can harm plant growth by increasing the concentration of soluble salts in the root zone, thereby creating osmotic stress and ion toxicity (Munns, 2005). Soil salinity levels, measured as electrical conductivity (EC) in decisiemens per meter (dS/m), are classified into five categories based on their impact on crop yields:

Table 1: Soil Salinity classes in terms of electrical conductivity (EC)

EC (dS/m)	Salinity Class	Effects on Crops
< 2	Non-saline	Salinity effects are negligible.
2–4	Slightly saline	Yields of very sensitive crops may be restricted.
4–8	Moderately saline	Yields of many crops are restricted.
8–16	Very saline	Only tolerant crops yield satisfactorily.
> 16	Extremely saline	Only a few very tolerant crops yield satisfactorily

This classification highlights the importance of managing soil salinity to prevent yield losses, particularly in sensitive crops. Proper soil and water management practices can help mitigate salinity issues and support agricultural productivity (Richards, 1954).

Soil salinity negatively affects plant growth through multiple mechanisms:

Reduced Water Uptake: High salt concentrations in the soil create osmotic stress, making it difficult for plants to absorb water, leading to dehydration (Razzaghi et al., 2011).

Nutrient Imbalance: Sodium ions (Na^+) compete with essential cations like potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), disrupting nutrient uptake and causing imbalances that impair vital physiological processes (Zhu, 2002).

Toxic Ion Accumulation: Excess sodium (Na^+) and chloride (Cl^-) ions can accumulate in plant tissues, reaching toxic levels that disrupt cellular functions, damage membranes, and interfere with processes such as photosynthesis and respiration. Symptoms of toxicity include leaf burn, necrosis, and chlorosis (Chele et al., 2021).

Overall, soil salinity reduces plant vigor, stunts growth, and lowers productivity, emphasizing the need for effective salinity management to sustain plant health and yield.

Plant Affinity for Nutrients and Ion Transport

Plants utilize high-affinity and low-affinity transport systems to absorb nutrients and ions essential for growth. High-affinity transporters function effectively under low substrate concentrations, ensuring nutrient uptake even when resources are scarce. In contrast, low-affinity systems operate efficiently at higher substrate concentrations (Dreyer & Michard, 2020).

The following table highlights plants with notable high-affinity transport mechanisms for specific nutrients:

Table 2: plant species with high-affinity mechanisms for specific nutrients or ions

Plant Species	Nutrient/Ion	Reference
Barley (*Hordeum vulgare L.*)	Potassium	(Epstein et al., 1963)
Maize (*Zea mays L.*)	Nitrogen (Ammonium)	(Gu et al., 2013)
Spinach (*Spinacia oleracea L.*)	Calcium	(Kreimer et al., 1987)
Rice (*Oryza sativa L.*)	Nitrogen	(Feng et al., 2011)
Pea (*Pisum sativum*)	Nitrogen	(Werner & Newton, 2005)
Wheat (*Triticum aestivum*)	Phosphate	(Liu et al., 2013)
Cucumber (*Cucumis sativus*)	Copper	(Migocka et al., 2015)
Pepper (*Capsicum annuum*)	Potassium	(Martínez-Cordero et al., 2005)

These high-affinity transport mechanisms allow plants to efficiently absorb essential nutrients even at low concentrations, supporting their growth and development under nutrient-limited conditions.

Conclusion

Effective soil management is vital for optimizing plant growth and ensuring agricultural sustainability. Soil properties such as texture, structure, organic matter, pH, moisture, and salinity play crucial roles in nutrient availability and plant health. While clay soils retain nutrients but may hinder root growth, sandy soils promote root penetration yet require more fertilization. Organic matter improves soil fertility, while pH and salinity directly affect nutrient uptake and microbial activity, with extremes posing challenges like osmotic stress and ion toxicity. Tailored practices such as organic amendments, pH adjustments, and salinity control are essential for maintaining soil health. Future innovations in soil management can enhance fertility, resilience, and sustainability, contributing to food security and ecosystem conservation.

References

Allison, E., Jones, C., 2005. Plant water relations. Montana State University. Extension paper(4481-5), 7.

Andreux, F., 1996. Humus in world soils. In Humic substances in terrestrial ecosystems (pp. 45-100): Elsevier.

Arduini, I., Kettner, C., Godbold, D., Onnis, A., Stefani, A., 1998. pH influence on root growth and nutrient uptake of Pinus pinaster seedlings. Chemosphere, 36(4-5), 733-738.

Arunkumar, S., 2021. Soil Colloids and its Properties. AgriCos e-Newsletter.

Bashir, O., Khan, K., Hakeem, K.R., Mir, N.A., Rather, G.H., Mohiuddin, R., 2016. Soil microbe diversity and root exudates as important aspects of rhizosphere ecosystem. Plant, Soil and Microbes: Volume 2: Mechanisms and Molecular Interactions, 337-357.

Brundrett, M.C., 2009. Mycorrhizal associations and other means of nutrition of vascular plants: understanding the global diversity of host plants by resolving conflicting information and developing reliable means of diagnosis. Plant and Soil, 320, 37-77.

Burns, R.G., Slater, J.H., 1982. Experimental microbial ecology.

Butcher, K., Wick, A.F., DeSutter, T., Chatterjee, A., Harmon, J., 2016. Soil salinity: A threat to global food security. Agronomy Journal, 108(6), 2189-2200.

Chaney, K., Swift, R., 1984. The influence of organic matter on aggregate stability in some British soils. Journal of Soil science, 35(2), 223-230.

Chele, K.H., Tinte, M.M., Piater, L.A., Dubery, I.A., Tugizimana, F., 2021. Soil salinity, a serious environmental issue and plant responses: A metabolomics perspective. Metabolites, 11(11), 724.

Coleman, D.C., Cole, C., Hunt, H., Klein, D.A., 1977. Trophic interactions in soils as they affect energy and nutrient dynamics. I. Introduction. Microbial Ecology, 4, 345-349.

Dreyer, I., Michard, E., 2020. High-and low-affinity transport in plants from a thermodynamic point of view. Frontiers in Plant Science, 10, 512268.

El-Ghazlane, O., Mathiot, C., Alzraiee, A., Singh, P.A., Longley, K., Benes, S., 2017. Validation of the steady-state Hoffman conceptual model for determination of minimum crop leaching requirements and stakeholder outreach using csuid. Final Report. California State University.

Epstein, E., Rains, D., Elzam, O., 1963. Resolution of dual mechanisms of potassium absorption by barley roots. Proceedings of the National Academy of Sciences, 49(5), 684-692.

FAO. Soil organic matter. Retrieved from https://www.unescwa.org/sd-glossary/soil-organic-matter

Feng, H., Yan, M., Fan, X., Li, B., Shen, Q., Miller, A. J., Xu, G., 2011. Spatial expression and regulation of rice high-affinity nitrate transporters by nitrogen and carbon status. Journal of Experimental Botany, 62(7), 2319-2332.

Gondal, A.H., Hussain, I., Ijaz, A.B., Zafar, A., Ch, B.I., Zafar, H., Khan, A.A., 2021. Influence of soil pH and microbes on mineral solubility and plant nutrition: A review. International Journal of Agriculture and Biological Sciences, 5(1), 71-81.

Grossl, P.R., Inskeep, W.P., 1991. Precipitation of dicalcium phosphate dihydrate in the presence of organic acids. Soil Science Society of America Journal, 55(3), 670-675.

Gu, R., Duan, F., An, X., Zhang, F., von Wirén, N., Yuan, L., 2013. Characterization of AMT-mediated high-affinity ammonium uptake in roots of maize (Zea mays L.). Plant and Cell Physiology, 54(9), 1515-1524.

Hudson, B.D., 1994. Soil organic matter and available water capacity. Journal of soil and water conservation, 49(2), 189-194.

Jones, C., Jacobsen, J., 2005. Plant nutrition and soil fertility. Nutrient management module, 2(11), 1-11.

Klepper, B., 1992. Development and growth of crop root systems. In Limitations to plant root growth (pp. 1-25): Springer.

Konen, M., Burras, C., Sandor, J., 2003. Organic carbon, texture, and quantitative color measurement relationships for cultivated soils in north central Iowa. Soil Science Society of America Journal, 67(6), 1823-1830.

Kreimer, G., Surek, B., Woodrow, I.E., Latzko, E., 1987. Calcium binding by spinach stromal proteins. Planta, 171, 259-265.

Kumar, Y., Kaushal, D., Kaur, G., Gulati, D., 2020. Effect of soil organic matter on physical properties of soil. Just Agriculture, 1(2), 25-30.

Lambers, H., Raven, J.A., Shaver, G.R., Smith, S.E., 2008. Plant nutrient-acquisition strategies change with soil age. Trends in ecology & evolution, 23(2), 95-103.

Liu, X., Zhao, X., Zhang, L., Lu, W., Li, X., Xiao, K., 2013. TaPht1; 4, a high-affinity phosphate transporter gene in wheat (Triticum aestivum), plays an important role in plant phosphate acquisition under phosphorus deprivation. Functional Plant Biology, 40(4), 329-341.

Lynch, J.M., Brimecombe, M.J., De Leij, F.A., 2001. Rhizosphere. e LS.

Lynch, J.P., Strock, C.F., Schneider, H.M., Sidhu, J.S., Ajmera, I., Galindo-Castañeda, T., Hanlon, M.T., 2021. Root anatomy and soil resource capture. Plant and Soil, 466, 21-63.

Martínez-Cordero, M.A., Martínez, V., Rubio, F., 2005. High-affinity K+ uptake in pepper plants. Journal of Experimental Botany, 56(416), 1553-1562.
McCauley, A., Jones, C., Jacobsen, J., 2009. Soil pH and organic matter. Nutrient management module, 8(2), 1-12.
Migocka, M., Posyniak, E., Maciaszczyk-Dziubinska, E., Papierniak, A., Kosieradzaka, A., 2015. Functional and biochemical characterization of cucumber genes encoding two copper ATPases CsHMA5. 1 and CsHMA5. 2. Journal of Biological Chemistry, 290(25), 15717-15729.
Munns, R., 2005. Genes and salt tolerance: bringing them together. New Phytologist, 167(3), 645-663.
NRCS. Soil. Retrieved from https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soil
Pierret, A., Moran, C.J., Doussan, C., 2005. Conventional detection methodology is limiting our ability to understand the roles and functions of fine roots. New Phytologist, 166(3), 967-980.
Pietri, J. A., Brookes, P., 2008. Relationships between soil pH and microbial properties in a UK arable soil. Soil Biology and Biochemistry, 40(7), 1856-1861.
Rajendra Prasad, R.P., Power, J., 1997. Soil fertility management for sustainable agriculture.
Razzaghi, F., Ahmadi, S.H., Adolf, V.I., Jensen, C.R., Jacobsen, S.E., Andersen, M.N., 2011. Water relations and transpiration of quinoa (Chenopodium quinoa Willd.) under salinity and soil drying. Journal of agronomy and crop science, 197(5), 348-360.
Richards, L.A., 1954. Diagnosis and improvement of saline and alkali soils: US Government Printing Office.
Roy, R.N., Finck, A., Blair, G., Tandon, H., 2006. Plant nutrition for food security. A guide for integrated nutrient management. FAO Fertilizer and Plant Nutrition Bulletin, 16(368), 201-214.
Schroth, G., Sinclair, F.L., 2003. Trees, crops, and soil fertility: concepts and research methods: Cabi.
Veihmeyer, F., Hendrickson, A., 1927. Soil-moisture conditions in relation to plant growth. Plant physiology, 2(1), 71.
Walker, T.S., Bais, H.P., Grotewold, E., Vivanco, J.M., 2003. Root exudation and rhizosphere biology. Plant physiology, 132(1), 44-51.
Walter, A., Silk, W.K., Schurr, U., 2000. Effect of soil pH on growth and cation deposition in the root tip of Zea mays L. Journal of Plant Growth Regulation, 19, 65-76.
Wei, X., Xie, B., Wan, C., Song, R., Zhong, W., Xin, S., Song, K., 2024. Enhancing Soil Health and Plant Growth through Microbial Fertilizers: Mechanisms, Benefits, and Sustainable Agricultural Practices. Agronomy, 14(3), 609.
Werner, D., Newton, W.E., 2005. Nitrogen fixation in agriculture, forestry, ecology, and the environment (Vol. 4): Springer Science & Business Media.
Yu, C., Mawodza, T., Atkinson, B.S., Atkinson, J.A., Sturrock, C.J., Whalley, R., Zhou, H., 2024. The effects of soil compaction on wheat seedling root growth are specific to soil texture and soil moisture status. Rhizosphere, 29, 100838.
Zhu, J.K., 2002. Salt and drought stress signal transduction in plants. Annual review of plant biology, 53(1), 247-273.

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

Rhizosphere associated beneficial microbes and its dynamics in soil health and soil microbial diversity

Karun ADHIKARI *, Mariana PETKOVA

Faculty of Plant Protection, Department of Microbiology and Environmental Biotechnologies, Agricultural University Plovdiv, Bulgaria

***Corresponding Author**

Karun ADHİKARİ

karunadhikary45@gmail.com

Abstract

Microbial activity in the rhizosphere is a result of dynamic interaction between numerous components. Factors like soil type, plant species, and environmental conditions play crucial role in shifting the soil microbial community composition, which can enable proliferation & dominance of certain microbial taxonomic groups. Rhizosphere-associated beneficial microbes significantly influence plant protection, nutrient availability, nutrient foraging, and plant growth through multiple pathways. Due to their ubiquitous nature in soil, studying their presence and interaction with the rhizosphere and soil microbial community can provide context to their mechanisms and functioning. This review aims to contextualize the mechanism, and documented works associated with the role of beneficial microbes in the microbial community structure, and chemical and biological health of soil. Utilizing these beneficial microbes and their integration with appropriate managerial measures can be an effective alternative in improving soil microbial community composition, nutrient availability, microbial health and synthesis of bioactive compounds. Additionally, activities associated with beneficial microbes through antagonism, synthesis of compounds, competition, and production of enzymes could be understood better because of its link to the role in the microbial community shift. The functioning of soil biology is dependent upon the activity of the microbial community in the soil. Studying their presence and dominance over other microbial groups can be crucial in assessing soil microbial health. This review also focuses on the activities and mechanisms adopted by beneficial microbes in soil that affect plant and soil health and appropriate the overall functioning of the microbiome.

Keywords: Rhizosphere, Microbial community, Biological, Soil Health, Metagenomics

Introduction

The rhizosphere is a complex interactive interface between plant roots and the surrounding soil, directly under the influence of the plant roots, where multiple components exert influence on the other (Oburger & Schmidt, 2016; Kennedy & Luna, 2005). This zone, typically only a few millimeters from the plant root, is characterized by elevated interactions among roots, microbes, and fauna. Interactions between these components can vary widely vary from being beneficial to plants and microbes to antagonistic with pathogens. Other interactions include processes like symbiotic Nitrogen fixation, pathogenic attack, mycorrhizal relationship, mechanisms for nutrient acquisition, and alleviation of soil toxicity (Veerapagu et al., 2023; Hu et al., 2021; Trivedi et al., 2012).

The presence of a higher microbiome diversity and population is largely due to the availability of exudates and rhizodeposits, chemical signalling and particularly the ability of these microbes to utilize the rhizodeposits (Malhotra & Srivastava, 2009). Rhizodeposits and the root exudates are a complex combination composed of organic acids, sugar, vitamins, amino acids, enzymes, degraded cell components etc. which plays an important role in the assimilation of microbial population in the rhizosphere. It is affected by multiple mechanisms. The chemical signalling by plant roots is another factor that plays an active role and drives as an attractant (Dakora & Phillips, 2002).

Rhizospheric microbial communities are involved in the overall soil functioning due to their involvement in organic matter decomposition, antagonism to pathogens, nutrient availability, soil aggregation, nutrient cycling, availability of organic compounds etc. (Cardon and Whitbeck, 2011; Abiven et al., 2007). Their role is vast and it requires extensive research to underline the specific mechanisms. However, due to the complexity of soil microbial ecosystems, understanding the specific functions and interactions within these microbial communities is difficult. Over the years, as the drawbacks of conventional soil management practices have become increasingly apparent, there has been a shift towards alternative approaches that have relatively less impact on the soil and the ecosystem. One such approach is the use of beneficial microbes associated with the rhizosphere, which supports sustainable soil management and promotes ecosystem health.

This assimilation through various mechanisms in the rhizosphere means that the rhizosphere is home to diverse range of microorganisms, including beneficial microbes like proteobacteria, firmicutes, Deuteromycetes, Sebacinales, as well as plant pathogenic microbes including nematodes apart from fungal and bacterial species, with instances of human pathogenic microbes (Mendes et al., 2013). Among all the rhizosphere species, numerous beneficial species have been isolated to study their role in plant growth, soil health, and microbial activity. Use of the ascertained beneficial microbes in bulk soil has indicated some positive results in soil nutrients, plant growth and protection and have been commercialized as biofertilizers and biocontrol agents (Cano-Castro et al., 2024; Rashad et al., 2023; Yang et al., 2024; Qin et al., 2019; Tian et al., 2023).

The keystone taxa in the rhizosphere- microbes that significantly influence microbial community composition- also indicate the same. These microbes are strongly linked to the availability of soil nutrients and more so to the soil properties (Wei et al., 2023). The diverse presence of microbes underscores the need for further research to understand how beneficial microbes function under stress conditions and under the presence of other antagonistic microbes. Such studies are crucial to explore microbial soil functioning, and its role in plant growth while maintaining the microbial community composition in soil.

Microbial Community Structure

The rhizospheric Microbial Community structure is a dynamic and complex hotspot of microbial activity with numerous interactions. Among many others, the community is influenced by soil type, plant species, and location of the root zone (Marschner et al., 2001). Besides, since plant species, and soil type can affect the soil microbial community, the mechanism adopted by beneficial microbes (even if it is site-specific) (Philippot et al., 2013) against pathogens, will inevitably have impact on the overall structure, including the presence or dominance of certain microbial taxa. In addition, environmental conditions and agricultural practices, such as the tillage practices, and the application of chemical fertilizers and pesticides significantly affect the functionality and working of rhizospheric microbes (Omotayo and Babalola, 2021). In this context, metagenomic studies can be one of the crucial steps in understanding the response of human activities in soil.

In line with how rhizospheric microbial diversity is affected, endophytic microbiomes in plants are also largely shaped by the plant species and environmental factors (Pais et al., 2024) which dictates their exhibition and role in an ecosystem. Furthermore, bacterial diversity also plays an important role in regulating the soil function and plant species. The presence of pathogens in the rhizosphere can also shift the rhizospheric microbial community composition (Trivedi et al., 2012). The change observed in the diversity of the dynamic microbiome population is complex and hence requires nuanced comprehension of how microbial populations respond to varying conditions in the soil.

Rhizosphere Microbial Community and Beneficial Microbes

Research on the use of beneficial microbes has been going on for a many years. The positive effects on plant growth and antagonistic activity against pathogens in soil have been documented over time (Kashyap et al., 2019; Calvo et al., 2010). Particularly, the mechanisms are a synthesis of compounds, antagonism, competition etc. and other associated changes. Microbes in the rhizosphere are extremely dynamic and adapt to the changing surrounding conditions (Ling et al., 2022). This is one of the primary reasons in the incidence of highly increased or reduced microbial diversity in changing conditions of diseased soil environment, or under abiotic stress.

In such instances of diseased soil environments or under abiotic stress, the presence of beneficial microbes induces production of bioactive compounds, hydrolytic enzymes, and many other metabolites which help maintain the microbial community structure and plant yield. These beneficial microbes are crucially linked to plant growth-promotion via several mechanisms, including the production of phytohormones like auxin, cytokinins, gibberellins, along with the ability to solubilize nutrients like zinc and iron, and have other multiple indirect positive effects (Cassán et al., 2014). Their production of catalytic enzymes and lytic compounds is also linked with defence against fungal and bacterial pathogens.

The activity associated with beneficial microbes isolated from the rhizosphere are especially crucial in conditions of a C-limiting, N-limiting environment. In such nutrient-limited conditions, certain rhizosphere-linked bacteria triggers better or sustained production of phytohormones like indole 3-acetic acid (IAA) which is an indication of their ability to endure harsh condition and competitive nature in the rhizosphere (Malhotra & Srivastava, 2009; Ona et al., 2005). This combination of adaptability to nutrient-limiting conditions and plant growth-promoting ability makes beneficial microbes an alternative and integrates them with other sustainable approaches.

Rhizospheric Microbial Community and Plant Pathogen

The presence of plant pathogenic microbes in the rhizosphere can reduce soil microbial diversity, primarily through the production of toxic substances and competition (Xiao et al., 2024). Certain taxonomic groups of rhizospheric microbes are more abundant in healthy soils compared to diseased soils, suggesting their role in pathogen prevention. This relationship between plants and these specific microbial groups likely contributes to the prevention and reduced abundance of pathogens. For instance, a higher abundance of Actinobacteria found in healthy soil is associated with their role in disease prevention as compared to their lower presence in diseased soils (Hazarika & Thakur, 2020).

This could also be a result of root-produced exopolysaccharides that act as a binding agent to beneficial microbes (Czaczyk & Myszka, 2007). However, this alone may present a risk of pathogenic microbe being associated with these compounds, so it is likely that a combination of organic compound synthesis, along with other associated mechanisms plays a role in disease supression. Since all these processes occur at the root-soil interface, it has multifolds of effects on the accompanying microbiome and soil health.

Rhizospheric Microbial activity and Compound Production

The synthesis of Indole Acetic Acid has been linked with various rhizospheric microbes including Bacillus sp, Azospirillum sp, Pseudomonas sp etc. (Figueiredo et al., 2010; Larekeng et al., 2020). Species within Lactobacillales order have been associated with the production of root-promoting compounds and their presence has been observed in diverse environments through metagenomic sequencing analysis. (Maki et al., 2021). Metagenomics can provide crucial insights into characterizing these microbial groups of beneficial species by sequencing their genetic primers.

The bacterial community composition can be an indicator in understanding the pathogen-induced changes. During a pathogen attack, the rhizosphere is predominately colonized by increased bacterial species despite the similarity between non-infected and infected rhizosphere being high (Yang et al., 2001). Moreover, rhizobacterial production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase enzyme and its role in reducing of ethylene production in roots has been established. Since, ethylene production in root retards its growth, rhizobacteria break down ACC into α-ketobutyrate and ammonia, using them as carbon and nitrogen sources for promoting microbial activity and root elongation (Vessey et al., 2003; Singh et al., 2022).

Microbial Community in Abiotic Stress

Masmoudi et al., (2021) found that in abiotic stress related to drought and saline soil conditions, plant species cope with the condition by assembling bacterial groups that help in their growth and protection. In particular, the Gammaproteobacteria and Alphaproteobacteria classes were the dominating classes in the bacterial microbiomes associated with the plants. Rhizosphere-associated bacteria can increase 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase activity to alleviate saline salt-induced tolerance, and improve root growth in seedlings (Gupta and Pandey, 2019). Activities linked to these mechanisms would be understood better by characterizing the microbes involved in these processes.

In addition to this, beneficial rhizobacteria in the soil employ several adaptive strategies to cope with abiotic stress. These strategies include membrane modification, production of protectivecompounds, and reduced growth, in some cases (Valencia-Marin et al., 2023).

Microbial Community and Plant Nutrition

Diverse microbes associated with the rhizosphere function through multiple mechanisms and help enhance nutrient availability. For instance, bacteria from Rhizobiales order help fix atmospheric nitrogen under N-limiting conditions by triggering specific chemical pathways. Alongside, the production of flavinoids, organic acids and other compounds by plants may act as attractants to the nodule-forming bacteria in Rhizobia-Legume symbiosis (Dakora & Phillips, 2002). Beneficial bacteria from Bacillus species have multifolds of effects on growth-associated hormones like indole acetic acid, gibberellic acid, and brassinosteroid along with biocontrol hormones. These effects are due to the involvement of genes linked to hormone synthesis and by altering the composition of the microbial diversity where plant growth promoting bacterial population increases (Qin et al., 2021).

In addition, beneficial bacteria and fungi in the rhizosphere produce siderophores under Iron-limiting conditions. These siderophores work either by scavenging trace iron or in combination with plant-produced compounds that solubilize otherwise insoluble iron (Hider & Kong, 2009). Phyla such as Proteobacteria and Ascomycota are strongly associated with labile carbon availability in the soil because of their role in extracellular enzyme production, and organic matter decomposition in the soil (Campbell et al., 2022). Certain phosphate-solubilizing bacteria in the rhizosphere can solubilize insoluble phosphate through the production of organic acids, and extracellular enzymes, modifying the rhizospheric pH, and by working in association with the plant root. It is particularly important due to the problem associated with the presence of phosphorus but in unavailable form since it has tendency to form insoluble complexes with other elements (Mengel et al., 2001).

Factors limiting the growth of microbial populations composed primarily of Bacteria and fungi are also important. For example, mostly in C-limiting conditions, bacterial growths are found to be the main factor limiting their growth. However, some studies have found that even at nutrient-limiting conditions, the production of phytohormones is sustained (Aldén et al., 2001).

Since bacterial species are organotrophs in the rhizosphere, a higher abundance of beneficial fungal and bacterial species is crucial for its role in decomposition and nutrient assimilation. The beneficial activities associated with these microbes in soil may be more prominent if the soils and crops are inoculated with isolated beneficial microbes at a higher concentration in the field. This can enhance the association of plant-microbe interaction, increase the soil microbial diversity and support the sustained proliferation of beneficial microbe (Wei et al., 2024; Araujo et al., 2020).

Metagenomics in Microbial Diversity

Rhizosphere-associated microbial activity and diversity are influenced by a multiple factor. This shaping of the microbial structure in soil can be understood better by metagenomic studies. Metagenomics can offer insights into how the enzymatic activities, decomposition, and nutrient acquisition are affected by the shifts in composition of microbial population. These shifts, such as the reduction or dominance of certain population can impact soil health quality. For example, Marcheva et al., (2024) found that intercropping systems with legume led to a significant increase in bacterial species diversity, including beneficial microbes associated with nitrogen fixation and phosphate solubilization, which had significant impact on the rhizosphere. Similarly, Liao et al., (2024) also found that even in intercropping of nonlegumes like chrysanthemum and maize, enhanced the number of beneficial microorganisms linked with improved crop yield traits and better soil physiochemical properties showcasing better results compared to monoculturing.

Metagenomic studies can play crucial role in identification and characterization of microbiomes associated with specific activities, providing significant direction for microbiological studies in soil (Wani et al., 2022). The quantification and the diversity assessment of microbial population in soil through genomic sequencing can help ascertain the functional role of specific microbial groups in soil. For instance, Petkova and Shilev (2023) found a significantly higher fungal diversity in thermophilic environment during composting indicating their activity at higher temperature as reveled through metagenomic sequencing. This differences in the mesophilic environment and thermophilic environment with varied activity and diversity accredited to the presence of microbes from the specific group help decipher their role in the environment during decomposition. Interestingly, enzymatic activity linked to carbon cycling was higher in the mesophilic environment meaning the microbes involved in carbon cycling are less active under a thermophilic environment.

Similarly, metagenomic analysis by Wang et al., (2023) found that with continuous monoculture of Casuarina equisetifolia, the number of microorganisms from the dominant species of Actinoallomurus, Actinomadura and Mycobacterium reduced in the rhizosphere. This reduction in microbial diversity resulted in exposure of the plants to reduced protection from environmental stress. It further resulted in lower Microbial Biomass Carbon and Microbial Biomass Nitrogen, as well as a sharp decline in enzymatic activities and other metabolic processes in the soil.

Conclusion

The microbial activity in the rhizosphere is a dynamic mix of processes influenced bynumerous factors including soil type, plant species, and the presence of specific microbial species. Microbial diversity in soil is regulated and determined by these factors, as well as by soil management measures and environmental conditions. The functioning of soil biology is dependent upon the activity of the microbial community in the soil. The soil microbial community can be understood better by studying the activity of the microbial organisms present in the soil. Certainly, metagenomic studies offer a promising approcah to unravel how certain microbial groups are dominate the soil processes, owing to their mechanisms in overpowering other microbial groups.

Rhizosphere-associated beneficial microbes play a key role in the functioning of soil mechanisms linked to fertility, biological health and plant growth. Characterizing the fungal and bacterial communities in the soil is crucial to understanding the role of these fungal and bacterial groups in soil health. Investigating the beneficial microbes already present in the rhizosphere, as well as their targeted application in the soil can help us explore their role and their effect on the soil dynamics. Moreover, it is important to know how these beneficial microbes shift the overall microbial community structure of the soil after their introduction. Coupling microbiome characterization and understanding their role in soil microbial community shift with other associated research on the production of enzymes, and microbe-mediated processes will provide a more comprehensive understandingof the role of the rhizosphere-associated beneficial microbes in soil health.

References

Abiven, S., Menasseri, S., Angers, D. A., Leterme, P., 2007. Dynamics of aggregate stability and biological binding agents during decomposition of organic materials. European Journal of Soil Science, 58(1), 239-247. https://doi.org/10.1111/j.1365-2389.2006.00833.x

Aldén, L., Demoling, F., Baath, E., 2001. Rapid method of determining factors limiting bacterial growth in soil. Applied and environmental microbiology, 67(4), 1830-1838. https://doi.org/10.1128/AEM.67.4.1830-1838.2001

Araujo, R., Dunlap, C., Franco, C. M., 2020. Analogous wheat root rhizosphere microbial successions in field and greenhouse trials in the presence of biocontrol agents Paenibacillus peoriae SP9 and Streptomyces fulvissimus FU14. Molecular plant pathology, 21(5), 622-635. https://doi.org/10.1111/mpp.12918

Campbell, T.P., Ulrich, D.E., Toyoda, J., Thompson, J., Munsky, B., Albright, M.B., Bailey, V.L., Tfaily, M.M., Dunbar, J., 2022. Microbial communities influence soil dissolved organic carbon concentration by altering metabolite composition. Frontiers in Microbiology, 12, 799014. https://doi.org/10.3389/fmicb.2021.799014

Cano-Castro, L., Li, J., Wang, N., Strauss, S. L., Schumann, A. W., 2024. Enhancing nutrient uptake and grapefruit (Citrus paradisi) growth through soil application of beneficial bacteria (Bacillus spp.). Frontiers in Horticulture, 3, 1383013. https://doi.org/10.3389/fhort.2024.1383013

Cardon, Z. G., & Whitbeck, J. L. (Eds.)., 2011. The rhizosphere: an ecological perspective. Elsevier.

Cassán, F., Vanderleyden, J., Spaepen, S., 2014. Physiological and agronomical aspects of phytohormone production by model plant-growth-promoting rhizobacteria (PGPR) belonging to the genus Azospirillum. Journal of Plant Growth Regulation, 33, 440-459.

Czaczyk K., Myszka K., 2007. Biosynthesis of extracellular polymeric substances (EPS) and its role in microbial biofilm formation. Polish J Environmental Studies 16.

Dakora, F. D., Phillips, D. A., 2002. Root exudates as mediators of mineral acquisition in low-nutrient environments. Food security in nutrient-stressed environments: exploiting plants' genetic capabilities, 201-213. https://doi.org/10.1007/978-94-017-1570-6_23

Figueiredo, M. D. V. B., Seldin, L., de Araujo, F. F., Mariano, R. D. L. R., 2011. Plant growth promoting rhizobacteria: fundamentals and applications. Plant growth and health promoting bacteria, 21-43. https://doi.org/10.1007/978-3-642-13612-2_2

Gupta, S., Pandey, S., 2019. ACC deaminase producing bacteria with multifarious plant growth promoting traits alleviates salinity stress in French bean (Phaseolus vulgaris) plants. Frontiers in microbiology, 10, 1506.

Hazarika, S. N., Thakur, D., 2020. Actinobacteria. In Beneficial microbes in agro-ecology (pp. 443-476). Academic Press. https://doi.org/10.1016/B978-0-12-823414-3.00021-6

Hider, R. C., Kong, X., 2010. Chemistry and biology of siderophores. Natural product reports, 27(5), 637-657. https://doi.org/10.1039/B906679A

Hu, Y., Qiu, L., Zhang, Z., Liu, K., Xia, X., Xiong, S., Zhao, S., Zhao, Z., Hu, Y., Liang, Y., 2021. Control of Streptomyces alfalfae XY25 T over clubroot disease and its effect on rhizosphere microbial community in Chinese cabbage field trials. Frontiers in microbiology, 12, 641556.

Kennedy, A. C., de Luna, L. Z., 2005. Rhizospher. Encyclopedia of Soils in the Environment, 399–406. https://doi.org/10.1016/B0-12-348530-4/00163-6

Larekeng, S. H., Achmad, F., (2020, October). Production of IAA hormone in rhizosphere bacterial isolates of community forest stands. In IOP Conference Series: Earth and Environmental Science (Vol. 575, No. 1, p. 012022). IOP Publishing. https://doi.org/10.1088/1755-1315/575/1/012022

Liao, Z., Chen, Q., Li, J., Wei, L., Wu, J., Wang, X., Liu, Q., Miao, Y., Liu, D., 2024. Influence of Chrysanthemum morifolium-maize intercropping pattern on yield, quality, soil condition, and rhizosphere soil microbial communities of C. morifolium. Frontiers in Plant Science, 15, 1383477.

Ling, N., Wang, T., Kuzyakov, Y., 2022. Rhizosphere bacteriome structure and functions. Nature communications, 13(1), 836. https://doi.org/10.1038/s41467-022-28448-9

Maki, Y., Soejima, H., Kitamura, T., Sugiyama, T., Sato, T., Watahiki, M. K., Yamaguchi, J., 2021. 3-Phenyllactic acid, a root-promoting substance isolated from Bokashi fertilizer, exhibits synergistic effects with tryptophan. Plant Biotechnology, 38(1), 9-16. https://doi.org/10.5511/plantbiotechnology.20.0727a

Malhotra, M., Srivastava, S., 2009. Stress-responsive indole-3-acetic acid biosynthesis by Azospirillum brasilense SM and its ability to modulate plant growth. European journal of soil biology, 45(1), 73-80. https://doi.org/10.1016/j.ejsobi.2008.05.006

Marcheva, M., Petkova, M., Slavova, V., Popov, V., 2024. Positive Effect of Camelina Intercropping with Legumes on Soil Microbial Diversity by Applying NGS Analysis and Mobile Fluorescence Spectroscopy. Applied Sciences, 14(19), 9046. https://doi.org/10.3390/app14199046

Marschner, P., Yang, C. H., Lieberei, R., Crowley, D. E., 2001. Soil and plant specific effects on bacterial community composition in the rhizosphere. Soil biology and Biochemistry, 33(11), 1437-1445.

Masmoudi, K., Aziz, M. A., Shamim, A., Sabeem, M., Hazzouri, K. M., Amiri, K. M., 2021. Metagenomics of beneficial microbes in abiotic stress tolerance of date palm. In The Date Palm Genome, Vol. 2: Omics and Molecular Breeding (pp. 203-214). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-73750-4_10

Mendes, R., Garbeva, P., Raaijmakers, J. M., 2013. The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. FEMS microbiology reviews, 37(5), 634-663. https://doi.org/10.1111/1574-6976.12028

Mengel, K., Kirkby, E.A., Kosegarten, H., Appel, T., 2001. Phosphorus. In: Mengel, K., Kirkby, E.A., Kosegarten, H., Appel, T. (eds) Principles of Plant Nutrition. Springer, Dordrecht. https://doi.org/10.1007/978-94-010-1009-2_9

Omotayo, O. P., Babalola, O. O., 2021. Resident rhizosphere microbiome's ecological dynamics and conservation: towards achieving the envisioned sustainable development goals, a review. International Soil and Water Conservation Research, 9(1), 127-142. https://doi.org/10.1016/j.iswcr.2020.08.002

Ona, O., Van Impe, J., Prinsen, E., Vanderleyden, J., 2005. Growth and indole-3-acetic acid biosynthesis of Azospirillum brasilense Sp245 is environmentally controlled. FEMS Microbiology Letters, 246(1), 125-132. https://doi.org/10.1016/j.femsle.2005.03.048

Pais, A., Ristaino, J., Whetten, R., Xiang, Q. Y., 2024. Metagenomic study reveals hidden relationships among fungal diversity, variation of plant disease, and genetic distance in Cornus florida (Cornaceae). Frontiers in Plant Science, 14, 1282188. https://doi.org/10.3389/fpls.2023.1282188

Petkova, M., & Shilev, S., 2023. Revealing Fungal Diversity in Mesophilic and Thermophilic Habitats of Sewage Sludge Composting by Next-Generation Sequencing. Applied Sciences, 13(9), 5546.

Philippot, L., Raaijmakers, J. M., Lemanceau, P., Van Der Putten, W. H., 2013. Going back to the roots: the microbial ecology of the rhizosphere. Nature reviews microbiology, 11(11), 789-799. https://doi.org/10.1038/nrmicro3109

Qin, L., Tian, P., Cui, Q., Hu, S., Jian, W., Xie, C., Yang, X., Shen, H., 2021. Bacillus circulans GN03 alters the microbiota, promotes cotton seedling growth and disease resistance, and increases the expression of phytohormone synthesis and disease resistance-related genes. Frontiers in Plant Science, 12, 644597. https://doi.org/10.3389/fpls.2021.644597

Rashad, Y. M., Al Tami, M. S., Abdalla, S. A., 2023. Eliciting transcriptomic and antioxidant defensive responses against Rhizoctonia root rot of sorghum using the endophyte Aspergillus oryzae YRA3. Scientific Reports, 13(1), 19823. https://doi.org/10.1038/s41598-023-46696-7

Singh, R. P., Ma, Y., Shadan, A., 2022. Perspective of ACC-deaminase producing bacteria in stress agriculture. Journal of Biotechnology, 352, 36-46. https://doi.org/10.1016/j.jbiotec.2022.05.002

Tian, L., Zhang, W., Zhou, G.D., Li, S., Wang, Y., Yang, B., Bai, T., Fan, H., He, P., Zheng, S.J., 2023. A biological product of Bacillus amyloliquefaciens QST713 strain for promoting banana plant growth and modifying rhizosphere soil microbial diversity and community composition. Frontiers in Microbiology, 14, 1216018. https://doi.org/10.3389/fmicb.2023.1216018

Trivedi, P., He, Z., Van Nostrand, J. D., Albrigo, G., Zhou, J., Wang, N., 2012. Huanglongbing alters the structure and functional diversity of microbial communities associated with citrus rhizosphere. The ISME journal, 6(2), 363-383. https://doi.org/10.1038/ismej.2011.100

Valencia-Marin, M. F., Chávez-Avila, S., Guzmán-Guzmán, P., del Carmen Orozco-Mosqueda, M., de Los Santos-Villalobos, S., Glick, B. R., Santoyo, G., 2023. Survival strategies of Bacillus spp. in saline soils: Key factors to promote plant growth and health. Biotechnology Advances, 108303. https://doi.org/10.1016/j.biotechadv.2023.108303

Vessey, J. K. 2003. Plant growth promoting rhizobacteria as biofertilizers. Plant and soil, 255, 571-586. https://doi.org/10.1023/A:1026037216893

Wang, Y., Lin, S., Li, J., Jia, X., Hu, M., Cai, Y., Cheng, P., Li, M., Chen, Y., Lin, W., Wang, H., 2023. Metagenomics-based exploration of key soil microorganisms contributing to continuously planted Casuarina equisetifolia growth inhibition and their interactions with soil nutrient transformation. Frontiers in Plant Science, 14, 1324184. https://doi.org/10.3389/fpls.2023.1324184

Wani, A.K., Akhtar, N., Singh, R., Chopra, C., Kakade, P., Borde, M., Al-Khayri, J.M., Suprasanna, P., Zimare, S.B., 2022. Prospects of advanced metagenomics and meta-omics in the investigation of phytomicrobiome to forecast beneficial and pathogenic response. Molecular Biology Reports, 49(12), 12165-12179.

Wei, X., Fu, T., He, G., Zhong, Z., Yang, M., Lou, F., He, T., 2023. Characteristics of rhizosphere and bulk soil microbial community of Chinese cabbage (Brassica campestris) grown in Karst area. Frontiers in Microbiology, 14, 1241436. https://doi.org/10.3389/fmicb.2023.1241436

Wei, X., Xie, B., Wan, C., Song, R., Zhong, W., Xin, S., Song, K., 2024. Enhancing soil health and plant growth through microbial fertilizers: Mechanisms, benefits, and sustainable agricultural practices. Agronomy, 14(3), 609. https://doi.org/10.3390/agronomy14030609

Xiao, Y., Zhang, S., Li, H., Teng, K., Wu, S., Liu, Y., Yu, F., He, Z., Li, L., Li, L., Meng, D., 2024. Metagenomic insights into the response of soil microbial communities to pathogenic Ralstonia solanacearum. Frontiers in Plant Science, 15, 1325141.

Yang, Y., Hu, J., Wei, X., Huang, K., Li, C., Yang, G., 2024. Deciphering core microbiota in rhizosphere soil and roots of healthy and Rhizoctonia solani-infected potato plants from various locations. Frontiers in Microbiology, 15, 1386417. https://doi.org/10.3389/fmicb.2024.1386417

Yang, C. H., Crowley, D. E., Menge, J. A., 2001. 16S rDNA fingerprinting of rhizosphere bacterial communities associated with healthy and Phytophthora infected avocado roots. FEMS microbiology ecology, 35(2), 129-136. https://doi.org/10.1111/j.1574-6941.2001.tb00796.x

Rhizosphere associated beneficial microbes and its dynamics in soil health and soil microbial diversity

Karun ADHIKARI *, Mariana PETKOVA
Faculty of Plant Protection, Department of Microbiology and Environmental Biotechnologies, Agricultural University Plovdiv, Bulgaria

***Corresponding Author**

Karun ADHİKARİ
karunadhikary45@gmail.com

Abstract

Microbial activity in the rhizosphere is a result of dynamic interaction between numerous components. Factors like soil type, plant species, and environmental conditions play crucial role in shifting the soil microbial community composition, which can enable proliferation & dominance of certain microbial taxonomic groups. Rhizosphere-associated beneficial microbes significantly influence plant protection, nutrient availability, nutrient foraging, and plant growth through multiple pathways. Due to their ubiquitous nature in soil, studying their presence and interaction with the rhizosphere and soil microbial community can provide context to their mechanisms and functioning. This review aims to contextualize the mechanism, and documented works associated with the role of beneficial microbes in the microbial community structure, and chemical and biological health of soil. Utilizing these beneficial microbes and their integration with appropriate managerial measures can be an effective alternative in improving soil microbial community composition, nutrient availability, microbial health and synthesis of bioactive compounds. Additionally, activities associated with beneficial microbes through antagonism, synthesis of compounds, competition, and production of enzymes could be understood better because of its link to the role in the microbial community shift. The functioning of soil biology is dependent upon the activity of the microbial community in the soil. Studying their presence and dominance over other microbial groups can be crucial in assessing soil microbial health. This review also focuses on the activities and mechanisms adopted by beneficial microbes in soil that affect plant and soil health and appropriate the overall functioning of the microbiome.

Keywords: Rhizosphere, Microbial community, Biological, Soil Health, Metagenomics

Introduction

The rhizosphere is a complex interactive interface between plant roots and the surrounding soil, directly under the influence of the plant roots, where multiple components exert influence on the other (Oburger & Schmidt, 2016; Kennedy & Luna, 2005). This zone, typically only a few millimeters from the plant root, is characterized by elevated interactions among roots, microbes, and fauna. Interactions between these components can vary widely vary from being beneficial to plants and microbes to antagonistic with pathogens. Other interactions include processes like symbiotic Nitrogen fixation, pathogenic attack, mycorrhizal relationship, mechanisms for nutrient acquisition, and alleviation of soil toxicity (Veerapagu et al., 2023; Hu et al., 2021; Trivedi et al., 2012).

The presence of a higher microbiome diversity and population is largely due to the availability of exudates and rhizodeposits, chemical signalling and particularly the ability of these microbes to utilize the rhizodeposits (Malhotra & Srivastava, 2009). Rhizodeposits and the root exudates are a complex combination composed of organic acids, sugar, vitamins, amino acids, enzymes, degraded cell components etc. which plays an important role in the assimilation of microbial population in the rhizosphere. It is affected by multiple mechanisms. The chemical signalling by plant roots is another factor that plays an active role and drives as an attractant (Dakora & Phillips, 2002).

Rhizospheric microbial communities are involved in the overall soil functioning due to their involvement in organic matter decomposition, antagonism to pathogens, nutrient availability, soil aggregation, nutrient cycling, availability of organic compounds etc. (Cardon and Whitbeck, 2011; Abiven et al., 2007). Their role is vast and it requires extensive research to underline the specific mechanisms. However, due to the complexity of soil microbial ecosystems, understanding the specific functions and interactions within these microbial communities is difficult. Over the years, as the drawbacks of conventional soil management practices have become increasingly apparent, there has been a shift towards alternative approaches that have relatively less impact on the soil and the ecosystem. One such approach is the use of beneficial microbes associated with the rhizosphere, which supports sustainable soil management and promotes ecosystem health.

This assimilation through various mechanisms in the rhizosphere means that the rhizosphere is home to diverse range of microorganisms, including beneficial microbes like proteobacteria, firmicutes, Deuteromycetes, Sebacinales, as well as plant pathogenic microbes including nematodes apart from fungal and bacterial species, with instances of human pathogenic microbes (Mendes et al., 2013). Among all the rhizosphere species, numerous beneficial species have been isolated to study their role in plant growth, soil health, and microbial activity. Use of the ascertained beneficial microbes in bulk soil has indicated some positive results in soil nutrients, plant growth and protection and have been commercialized as biofertilizers and biocontrol agents (Cano-Castro et al., 2024; Rashad et al., 2023; Yang et al., 2024; Qin et al., 2019; Tian et al., 2023).

The keystone taxa in the rhizosphere- microbes that significantly influence microbial community composition- also indicate the same. These microbes are strongly linked to the availability of soil nutrients and more so to the soil properties (Wei et al., 2023). The diverse presence of microbes underscores the need for further research to understand how beneficial microbes function under stress conditions and under the presence of other antagonistic microbes. Such studies are crucial to explore microbial soil functioning, and its role in plant growth while maintaining the microbial community composition in soil.

Microbial Community Structure

The rhizospheric Microbial Community structure is a dynamic and complex hotspot of microbial activity with numerous interactions. Among many others, the community is influenced by soil type, plant species, and location of the root zone (Marschner et al., 2001). Besides, since plant species, and soil type can affect the soil microbial community, the mechanism adopted by beneficial microbes (even if it is site-specific) (Philippot et al., 2013) against pathogens, will inevitably have impact on the overall structure, including the presence or dominance of certain microbial taxa. In addition, environmental conditions and agricultural practices, such as the tillage practices, and the application of chemical fertilizers and pesticides significantly affect the functionality and working of rhizospheric microbes (Omotayo and Babalola, 2021). In this context, metagenomic studies can be one of the crucial steps in understanding the response of human activities in soil.

In line with how rhizospheric microbial diversity is affected, endophytic microbiomes in plants are also largely shaped by the plant species and environmental factors (Pais et al., 2024) which dictates their exhibition and role in an ecosystem. Furthermore, bacterial diversity also plays an important role in regulating the soil function and plant species. The presence of pathogens in the rhizosphere can also shift the rhizospheric microbial community composition (Trivedi et al., 2012). The change observed in the diversity of the dynamic microbiome population is complex and hence requires nuanced comprehension of how microbial populations respond to varying conditions in the soil.

Rhizosphere Microbial Community and Beneficial Microbes

Research on the use of beneficial microbes has been going on for a many years. The positive effects on plant growth and antagonistic activity against pathogens in soil have been documented over time (Kashyap et al., 2019; Calvo et al., 2010). Particularly, the mechanisms are a synthesis of compounds, antagonism, competition etc. and other associated changes. Microbes in the rhizosphere are extremely dynamic and adapt to the changing surrounding conditions (Ling et al., 2022). This is one of the primary reasons in the incidence of highly increased or reduced microbial diversity in changing conditions of diseased soil environment, or under abiotic stress.

In such instances of diseased soil environments or under abiotic stress, the presence of beneficial microbes induces production of bioactive compounds, hydrolytic enzymes, and many other metabolites which help maintain the microbial community structure and plant yield. These beneficial microbes are crucially linked to plant growth-promotion via several mechanisms, including the production of phytohormones like auxin, cytokinins, gibberellins, along with the ability to solubilize nutrients like zinc and iron, and have other multiple indirect positive effects (Cassán et al., 2014). Their production of catalytic enzymes and lytic compounds is also linked with defence against fungal and bacterial pathogens.

The activity associated with beneficial microbes isolated from the rhizosphere are especially crucial in conditions of a C-limiting, N-limiting environment. In such nutrient-limited conditions, certain rhizosphere-linked bacteria triggers better or sustained production of phytohormones like indole 3-acetic acid (IAA) which is an indication of their ability to endure harsh condition and competitive nature in the rhizosphere (Malhotra & Srivastava, 2009; Ona et al., 2005). This combination of adaptability to nutrient-limiting conditions and plant growth-promoting ability makes beneficial microbes an alternative and integrates them with other sustainable approaches.

Rhizospheric Microbial Community and Plant Pathogen

The presence of plant pathogenic microbes in the rhizosphere can reduce soil microbial diversity, primarily through the production of toxic substances and competition (Xiao et al., 2024). Certain taxonomic groups of rhizospheric microbes are more abundant in healthy soils compared to diseased soils, suggesting their role in pathogen prevention. This relationship between plants and these specific microbial groups likely contributes to the prevention and reduced abundance of pathogens. For instance, a higher abundance of Actinobacteria found in healthy soil is associated with their role in disease prevention as compared to their lower presence in diseased soils (Hazarika & Thakur, 2020).

This could also be a result of root-produced exopolysaccharides that act as a binding agent to beneficial microbes (Czaczyk & Myszka, 2007). However, this alone may present a risk of pathogenic microbe being associated with these compounds, so it is likely that a combination of organic compound synthesis, along with other associated mechanisms plays a role in disease supression. Since all these processes occur at the root-soil interface, it has multifolds of effects on the accompanying microbiome and soil health.

Rhizospheric Microbial activity and Compound Production

The synthesis of Indole Acetic Acid has been linked with various rhizospheric microbes including Bacillus sp, Azospirillum sp, Pseudomonas sp etc. (Figueiredo et al., 2010; Larekeng et al., 2020). Species within Lactobacillales order have been associated with the production of root-promoting compounds and their presence has been observed in diverse environments through metagenomic sequencing analysis. (Maki et al., 2021). Metagenomics can provide crucial insights into characterizing these microbial groups of beneficial species by sequencing their genetic primers.

The bacterial community composition can be an indicator in understanding the pathogen-induced changes. During a pathogen attack, the rhizosphere is predominately colonized by increased bacterial species despite the similarity between non-infected and infected rhizosphere being high (Yang et al., 2001). Moreover, rhizobacterial production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase enzyme and its role in reducing of ethylene production in roots has been established. Since, ethylene production in root retards its growth, rhizobacteria break down ACC into α-ketobutyrate and ammonia, using them as carbon and nitrogen sources for promoting microbial activity and root elongation (Vessey et al., 2003; Singh et al., 2022).

Microbial Community in Abiotic Stress

Masmoudi et al., (2021) found that in abiotic stress related to drought and saline soil conditions, plant species cope with the condition by assembling bacterial groups that help in their growth and protection. In particular, the Gammaproteobacteria and Alphaproteobacteria classes were the dominating classes in the bacterial microbiomes associated with the plants. Rhizosphere-associated bacteria can increase 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase activity to alleviate saline salt-induced tolerance, and improve root growth in seedlings (Gupta and Pandey, 2019). Activities linked to these mechanisms would be understood better by characterizing the microbes involved in these processes.

In addition to this, beneficial rhizobacteria in the soil employ several adaptive strategies to cope with abiotic stress. These strategies include membrane modification, production of protectivecompounds, and reduced growth, in some cases (Valencia-Marin et al., 2023).

Microbial Community and Plant Nutrition

Diverse microbes associated with the rhizosphere function through multiple mechanisms and help enhance nutrient availability. For instance, bacteria from Rhizobiales order help fix atmospheric nitrogen under N-limiting conditions by triggering specific chemical pathways. Alongside, the production of flavinoids, organic acids and other compounds by plants may act as attractants to the nodule-forming bacteria in Rhizobia-Legume symbiosis (Dakora & Phillips, 2002). Beneficial bacteria from Bacillus species have multifolds of effects on growth-associated hormones like indole acetic acid, gibberellic acid, and brassinosteroid along with biocontrol hormones. These effects are due to the involvement of genes linked to hormone synthesis and by altering the composition of the microbial diversity where plant growth promoting bacterial population increases (Qin et al., 2021).

In addition, beneficial bacteria and fungi in the rhizosphere produce siderophores under Iron-limiting conditions. These siderophores work either by scavenging trace iron or in combination with plant-produced compounds that solubilize otherwise insoluble iron (Hider & Kong, 2009). Phyla such as Proteobacteria and Ascomycota are strongly associated with labile carbon availability in the soil because of their role in extracellular enzyme production, and organic matter decomposition in the soil (Campbell et al., 2022). Certain phosphate-solubilizing bacteria in the rhizosphere can solubilize insoluble phosphate through the production of organic acids, and extracellular enzymes, modifying the rhizospheric pH, and by working in association with the plant root. It is particularly important due to the problem associated with the presence of phosphorus but in unavailable form since it has tendency to form insoluble complexes with other elements (Mengel et al., 2001).

Factors limiting the growth of microbial populations composed primarily of Bacteria and fungi are also important. For example, mostly in C-limiting conditions, bacterial growths are found to be the main factor limiting their growth. However, some studies have found that even at nutrient-limiting conditions, the production of phytohormones is sustained (Aldén et al., 2001).

Since bacterial species are organotrophs in the rhizosphere, a higher abundance of beneficial fungal and bacterial species is crucial for its role in decomposition and nutrient assimilation. The beneficial activities associated with these microbes in soil may be more prominent if the soils and crops are inoculated with isolated beneficial microbes at a higher concentration in the field. This can enhance the association of plant-microbe interaction, increase the soil microbial diversity and support the sustained proliferation of beneficial microbe (Wei et al., 2024; Araujo et al., 2020).

Metagenomics in Microbial Diversity

Rhizosphere-associated microbial activity and diversity are influenced by a multiple factor. This shaping of the microbial structure in soil can be understood better by metagenomic studies. Metagenomics can offer insights into how the enzymatic activities, decomposition, and nutrient acquisition are affected by the shifts in composition of microbial population. These shifts, such as the reduction or dominance of certain population can impact soil health quality. For example, Marcheva et al., (2024) found that intercropping systems with legume led to a significant increase in bacterial species diversity, including beneficial microbes associated with nitrogen fixation and phosphate solubilization, which had significant impact on the rhizosphere. Similarly, Liao et al., (2024) also found that even in intercropping of nonlegumes like chrysanthemum and maize, enhanced the number of beneficial microorganisms linked with improved crop yield traits and better soil physiochemical properties showcasing better results compared to monoculturing.

Metagenomic studies can play crucial role in identification and characterization of microbiomes associated with specific activities, providing significant direction for microbiological studies in soil (Wani et al., 2022). The quantification and the diversity assessment of microbial population in soil through genomic sequencing can help ascertain the functional role of specific microbial groups in soil. For instance, Petkova and Shilev (2023) found a significantly higher fungal diversity in thermophilic environment during composting indicating their activity at higher temperature as reveled through metagenomic sequencing. This differences in the mesophilic environment and thermophilic environment with varied activity and diversity accredited to the presence of microbes from the specific group help decipher their role in the environment during decomposition. Interestingly, enzymatic activity linked to carbon cycling was higher in the mesophilic environment meaning the microbes involved in carbon cycling are less active under a thermophilic environment.

Similarly, metagenomic analysis by Wang et al., (2023) found that with continuous monoculture of Casuarina equisetifolia, the number of microorganisms from the dominant species of Actinoallomurus, Actinomadura and Mycobacterium reduced in the rhizosphere. This reduction in microbial diversity resulted in exposure of the plants to reduced protection from environmental stress. It further resulted in lower Microbial Biomass Carbon and Microbial Biomass Nitrogen, as well as a sharp decline in enzymatic activities and other metabolic processes in the soil.

Conclusion

The microbial activity in the rhizosphere is a dynamic mix of processes influenced bynumerous factors including soil type, plant species, and the presence of specific microbial species. Microbial diversity in soil is regulated and determined by these factors, as well as by soil management measures and environmental conditions. The functioning of soil biology is dependent upon the activity of the microbial community in the soil. The soil microbial community can be understood better by studying the activity of the microbial organisms present in the soil. Certainly, metagenomic studies offer a promising approcah to unravel how certain microbial groups are dominate the soil processes, owing to their mechanisms in overpowering other microbial groups.

Rhizosphere-associated beneficial microbes play a key role in the functioning of soil mechanisms linked to fertility, biological health and plant growth. Characterizing the fungal and bacterial communities in the soil is crucial to understanding the role of these fungal and bacterial groups in soil health. Investigating the beneficial microbes already present in the rhizosphere, as well as their targeted application in the soil can help us explore their role and their effect on the soil dynamics. Moreover, it is important to know how these beneficial microbes shift the overall microbial community structure of the soil after their introduction. Coupling microbiome characterization and understanding their role in soil microbial community shift with other associated research on the production of enzymes, and microbe-mediated processes will provide a more comprehensive understandingof the role of the rhizosphere-associated beneficial microbes in soil health.

References

Abiven, S., Menasseri, S., Angers, D. A., Leterme, P., 2007. Dynamics of aggregate stability and biological binding agents during decomposition of organic materials. European Journal of Soil Science, 58(1), 239-247. https://doi.org/10.1111/j.1365-2389.2006.00833.x

Aldén, L., Demoling, F., Baath, E., 2001. Rapid method of determining factors limiting bacterial growth in soil. Applied and environmental microbiology, 67(4), 1830-1838. https://doi.org/10.1128/AEM.67.4.1830-1838.2001

Araujo, R., Dunlap, C., Franco, C. M., 2020. Analogous wheat root rhizosphere microbial successions in field and greenhouse trials in the presence of biocontrol agents Paenibacillus peoriae SP9 and Streptomyces fulvissimus FU14. Molecular plant pathology, 21(5), 622-635. https://doi.org/10.1111/mpp.12918

Campbell, T.P., Ulrich, D.E., Toyoda, J., Thompson, J., Munsky, B., Albright, M.B., Bailey, V.L., Tfaily, M.M., Dunbar, J., 2022. Microbial communities influence soil dissolved organic carbon concentration by altering metabolite composition. Frontiers in Microbiology, 12, 799014. https://doi.org/10.3389/fmicb.2021.799014

Cano-Castro, L., Li, J., Wang, N., Strauss, S. L., Schumann, A. W., 2024. Enhancing nutrient uptake and grapefruit (Citrus paradisi) growth through soil application of beneficial bacteria (Bacillus spp.). Frontiers in Horticulture, 3, 1383013. https://doi.org/10.3389/fhort.2024.1383013

Cardon, Z. G., & Whitbeck, J. L. (Eds.)., 2011. The rhizosphere: an ecological perspective. Elsevier.

Cassán, F., Vanderleyden, J., Spaepen, S., 2014. Physiological and agronomical aspects of phytohormone production by model plant-growth-promoting rhizobacteria (PGPR) belonging to the genus Azospirillum. Journal of Plant Growth Regulation, 33, 440-459.

Czaczyk K., Myszka K., 2007. Biosynthesis of extracellular polymeric substances (EPS) and its role in microbial biofilm formation. Polish J Environmental Studies 16.

Dakora, F. D., Phillips, D. A., 2002. Root exudates as mediators of mineral acquisition in low-nutrient environments. Food security in nutrient-stressed environments: exploiting plants' genetic capabilities, 201-213. https://doi.org/10.1007/978-94-017-1570-6_23

Figueiredo, M. D. V. B., Seldin, L., de Araujo, F. F., Mariano, R. D. L. R., 2011. Plant growth promoting rhizobacteria: fundamentals and applications. Plant growth and health promoting bacteria, 21-43. https://doi.org/10.1007/978-3-642-13612-2_2

Gupta, S., Pandey, S., 2019. ACC deaminase producing bacteria with multifarious plant growth promoting traits alleviates salinity stress in French bean (Phaseolus vulgaris) plants. Frontiers in microbiology, 10, 1506.

Hazarika, S. N., Thakur, D., 2020. Actinobacteria. In Beneficial microbes in agro-ecology (pp. 443-476). Academic Press. https://doi.org/10.1016/B978-0-12-823414-3.00021-6

Hider, R. C., Kong, X., 2010. Chemistry and biology of siderophores. Natural product reports, 27(5), 637-657. https://doi.org/10.1039/B906679A

Hu, Y., Qiu, L., Zhang, Z., Liu, K., Xia, X., Xiong, S., Zhao, S., Zhao, Z., Hu, Y., Liang, Y., 2021. Control of Streptomyces alfalfae XY25 T over clubroot disease and its effect on rhizosphere microbial community in Chinese cabbage field trials. Frontiers in microbiology, 12, 641556.

Kennedy, A. C., de Luna, L. Z., 2005. Rhizospher. Encyclopedia of Soils in the Environment, 399–406. https://doi.org/10.1016/B0-12-348530-4/00163-6

Larekeng, S. H., Achmad, F., (2020, October). Production of IAA hormone in rhizosphere bacterial isolates of community forest stands. In IOP Conference Series: Earth and Environmental Science (Vol. 575, No. 1, p. 012022). IOP Publishing. https://doi.org/10.1088/1755-1315/575/1/012022

Liao, Z., Chen, Q., Li, J., Wei, L., Wu, J., Wang, X., Liu, Q., Miao, Y., Liu, D., 2024. Influence of Chrysanthemum morifolium-maize intercropping pattern on yield, quality, soil condition, and rhizosphere soil microbial communities of C. morifolium. Frontiers in Plant Science, 15, 1383477.

Ling, N., Wang, T., Kuzyakov, Y., 2022. Rhizosphere bacteriome structure and functions. Nature communications, 13(1), 836. https://doi.org/10.1038/s41467-022-28448-9

Maki, Y., Soejima, H., Kitamura, T., Sugiyama, T., Sato, T., Watahiki, M. K., Yamaguchi, J., 2021. 3-Phenyllactic acid, a root-promoting substance isolated from Bokashi fertilizer, exhibits synergistic effects with tryptophan. Plant Biotechnology, 38(1), 9-16. https://doi.org/10.5511/plantbiotechnology.20.0727a

Malhotra, M., Srivastava, S., 2009. Stress-responsive indole-3-acetic acid biosynthesis by Azospirillum brasilense SM and its ability to modulate plant growth. European journal of soil biology, 45(1), 73-80. https://doi.org/10.1016/j.ejsobi.2008.05.006

Marcheva, M., Petkova, M., Slavova, V., Popov, V., 2024. Positive Effect of Camelina Intercropping with Legumes on Soil Microbial Diversity by Applying NGS Analysis and Mobile Fluorescence Spectroscopy. Applied Sciences, 14(19), 9046. https://doi.org/10.3390/app14199046

Marschner, P., Yang, C. H., Lieberei, R., Crowley, D. E., 2001. Soil and plant specific effects on bacterial community composition in the rhizosphere. Soil biology and Biochemistry, 33(11), 1437-1445.

Masmoudi, K., Aziz, M. A., Shamim, A., Sabeem, M., Hazzouri, K. M., Amiri, K. M., 2021. Metagenomics of beneficial microbes in abiotic stress tolerance of date palm. In The Date Palm Genome, Vol. 2: Omics and Molecular Breeding (pp. 203-214). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-73750-4_10

Mendes, R., Garbeva, P., Raaijmakers, J. M., 2013. The rhizosphere microbiome: significance of plant beneficial, plant pathogenic, and human pathogenic microorganisms. FEMS microbiology reviews, 37(5), 634-663. https://doi.org/10.1111/1574-6976.12028

Mengel, K., Kirkby, E.A., Kosegarten, H., Appel, T., 2001. Phosphorus. In: Mengel, K., Kirkby, E.A., Kosegarten, H., Appel, T. (eds) Principles of Plant Nutrition. Springer, Dordrecht. https://doi.org/10.1007/978-94-010-1009-2_9

Omotayo, O. P., Babalola, O. O., 2021. Resident rhizosphere microbiome's ecological dynamics and conservation: towards achieving the envisioned sustainable development goals, a review. International Soil and Water Conservation Research, 9(1), 127-142. https://doi.org/10.1016/j.iswcr.2020.08.002

Ona, O., Van Impe, J., Prinsen, E., Vanderleyden, J., 2005. Growth and indole-3-acetic acid biosynthesis of Azospirillum brasilense Sp245 is environmentally controlled. FEMS Microbiology Letters, 246(1), 125-132. https://doi.org/10.1016/j.femsle.2005.03.048

Pais, A., Ristaino, J., Whetten, R., Xiang, Q. Y., 2024. Metagenomic study reveals hidden relationships among fungal diversity, variation of plant disease, and genetic distance in Cornus florida (Cornaceae). Frontiers in Plant Science, 14, 1282188. https://doi.org/10.3389/fpls.2023.1282188

Petkova, M., & Shilev, S., 2023. Revealing Fungal Diversity in Mesophilic and Thermophilic Habitats of Sewage Sludge Composting by Next-Generation Sequencing. Applied Sciences, 13(9), 5546.

Philippot, L., Raaijmakers, J. M., Lemanceau, P., Van Der Putten, W. H., 2013. Going back to the roots: the microbial ecology of the rhizosphere. Nature reviews microbiology, 11(11), 789-799. https://doi.org/10.1038/nrmicro3109

Qin, L., Tian, P., Cui, Q., Hu, S., Jian, W., Xie, C., Yang, X., Shen, H., 2021. Bacillus circulans GN03 alters the microbiota, promotes cotton seedling growth and disease resistance, and increases the expression of phytohormone synthesis and disease resistance-related genes. Frontiers in Plant Science, 12, 644597. https://doi.org/10.3389/fpls.2021.644597

Rashad, Y. M., Al Tami, M. S., Abdalla, S. A., 2023. Eliciting transcriptomic and antioxidant defensive responses against Rhizoctonia root rot of sorghum using the endophyte Aspergillus oryzae YRA3. Scientific Reports, 13(1), 19823. https://doi.org/10.1038/s41598-023-46696-7

Singh, R. P., Ma, Y., Shadan, A., 2022. Perspective of ACC-deaminase producing bacteria in stress agriculture. Journal of Biotechnology, 352, 36-46. https://doi.org/10.1016/j.jbiotec.2022.05.002

Tian, L., Zhang, W., Zhou, G.D., Li, S., Wang, Y., Yang, B., Bai, T., Fan, H., He, P., Zheng, S.J., 2023. A biological product of Bacillus amyloliquefaciens QST713 strain for promoting banana plant growth and modifying rhizosphere soil microbial diversity and community composition. Frontiers in Microbiology, 14, 1216018. https://doi.org/10.3389/fmicb.2023.1216018

Trivedi, P., He, Z., Van Nostrand, J. D., Albrigo, G., Zhou, J., Wang, N., 2012. Huanglongbing alters the structure and functional diversity of microbial communities associated with citrus rhizosphere. The ISME journal, 6(2), 363-383. https://doi.org/10.1038/ismej.2011.100

Valencia-Marin, M. F., Chávez-Avila, S., Guzmán-Guzmán, P., del Carmen Orozco-Mosqueda, M., de Los Santos-Villalobos, S., Glick, B. R., Santoyo, G., 2023. Survival strategies of Bacillus spp. in saline soils: Key factors to promote plant growth and health. Biotechnology Advances, 108303. https://doi.org/10.1016/j.biotechadv.2023.108303

Vessey, J. K. 2003. Plant growth promoting rhizobacteria as biofertilizers. Plant and soil, 255, 571-586. https://doi.org/10.1023/A:1026037216893

Wang, Y., Lin, S., Li, J., Jia, X., Hu, M., Cai, Y., Cheng, P., Li, M., Chen, Y., Lin, W., Wang, H., 2023. Metagenomics-based exploration of key soil microorganisms contributing to continuously planted Casuarina equisetifolia growth inhibition and their interactions with soil nutrient transformation. Frontiers in Plant Science, 14, 1324184. https://doi.org/10.3389/fpls.2023.1324184

Wani, A.K., Akhtar, N., Singh, R., Chopra, C., Kakade, P., Borde, M., Al-Khayri, J.M., Suprasanna, P., Zimare, S.B., 2022. Prospects of advanced metagenomics and meta-omics in the investigation of phytomicrobiome to forecast beneficial and pathogenic response. Molecular Biology Reports, 49(12), 12165-12179.

Wei, X., Fu, T., He, G., Zhong, Z., Yang, M., Lou, F., He, T., 2023. Characteristics of rhizosphere and bulk soil microbial community of Chinese cabbage (Brassica campestris) grown in Karst area. Frontiers in Microbiology, 14, 1241436. https://doi.org/10.3389/fmicb.2023.1241436

Wei, X., Xie, B., Wan, C., Song, R., Zhong, W., Xin, S., Song, K., 2024. Enhancing soil health and plant growth through microbial fertilizers: Mechanisms, benefits, and sustainable agricultural practices. Agronomy, 14(3), 609. https://doi.org/10.3390/agronomy14030609

Xiao, Y., Zhang, S., Li, H., Teng, K., Wu, S., Liu, Y., Yu, F., He, Z., Li, L., Li, L., Meng, D., 2024. Metagenomic insights into the response of soil microbial communities to pathogenic Ralstonia solanacearum. Frontiers in Plant Science, 15, 1325141.

Yang, Y., Hu, J., Wei, X., Huang, K., Li, C., Yang, G., 2024. Deciphering core microbiota in rhizosphere soil and roots of healthy and Rhizoctonia solani-infected potato plants from various locations. Frontiers in Microbiology, 15, 1386417. https://doi.org/10.3389/fmicb.2024.1386417

Yang, C. H., Crowley, D. E., Menge, J. A., 2001. 16S rDNA fingerprinting of rhizosphere bacterial communities associated with healthy and Phytophthora infected avocado roots. FEMS microbiology ecology, 35(2), 129-136. https://doi.org/10.1111/j.1574-6941.2001.tb00796.x

Potential Effects of Biochar on Soil Properties of Calcareous Soil

Kazi Sanjida BEGUM*, Coşkun GÜLSER
Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Kazi Sanjida BEGUM
ksbegum.soil@gmail.com

Abstract
Calcareous soils, which are characterized by elevated levels of calcium carbonate ($CaCO_3$) and typically exhibit an alkaline pH, present unique challenges for soil management. These challenges include issues related to nutrient availability, water retention, root development, soil crusting, water infiltration, erosion, and microbial dynamics. The low organic matter content and alkaline pH in arid and semi-arid regions contribute to the limited nutrient availability for plants in these soils. To effectively manage the difficulties associated with calcareous soils, a combination of organic and inorganic practices tailored to the specific conditions of the soil and the requirements of the crops is often necessary. Among various organic amendments, biochar has emerged as a promising option due to its capacity to enhance soil fertility, boost nutrient retention, improve soil structure, and facilitate carbon sequestration. The impact of biochar on calcareous soil is influenced by factors such as pyrolysis temperature, biochar feedstock types, application rate, and soil texture. However, there is relatively limited literature specifically addressing the effects of biochar on the properties of calcareous soil. This paper aims to review recent developments in the application of biochar to calcareous soils and to discuss its effects on physical, chemical, and biological properties following its incorporation. While biochar can provide substantial benefits, it may also pose challenges related to soil pH, nutrient availability, and microbial activity. Therefore, careful management of biochar application is essential to prevent excessive pH increases and nutrient imbalances. Adjusting biochar production parameters, application rates, and combining it with other amendments may help mitigate some of these challenges.
Keywords: Biochar, calcareous soil, pyrolysis temperature, soil properties

Introduction
Calcareous soils cover over one-third of the global land area and are prevalent in many arid and semi-arid regions (Bolan et al., 2023). Their high concentrations of calcium carbonate ($CaCO_3$) lead to an alkaline pH (typically between 7.5 and 8.5), a low organic carbon content, and often a limited availability of essential nutrients, making them common in dry environments (Hasanpour et al., 2022). Despite their widespread occurrence, these soils present various challenges to agricultural productivity, primarily due to nutrient imbalances, deficiencies in phosphorus and trace elements (such as iron, zinc, and copper), the formation of surface crusts and compact subsurface layers, reduced microbial activity, and limited water retention (Bolan et al., 2023).

An emerging strategy to mitigate the adverse effects of calcareous soils is the application of biochar, which is a carbon-rich material produced by pyrolyzing organic matter at high temperatures in a low-oxygen environment (Hasanpour et al., 2022; Moradi et al., 2018). The addition of biochar as an organic amendment, known for its long-term stability, has garnered increased interest in recent decades due to its positive effects on soil chemical fertility and quality, as well as its potential for climate change mitigation (Masto et al., 2013a; Oliveira et al., 2017). Research indicates that biochar application can alter soil physical and chemical characteristics, leading to enhanced plant growth and productivity (Backer et al., 2016; Naeem et al., 2017) by improving the availability and retention of water and nutrients (Galvez et al., 2012; Ouyang et al., 2013), increasing soil aggregation and porosity (Du et al., 2017), and affecting both recalcitrant and labile organic carbon fractions as well as total nitrogen levels (Backer et al., 2016).

However, despite the wealth of published studies regarding the role of biochar in enhancing soil fertility and microbial activity, there is limited information on the relationship between soil nutrient status and microbial activity, particularly in the calcareous soils of arid regions with low organic matter content (Elzobair et al., 2016). The alkaline nature of these soils, characterized by high pH and calcium content, introduces specific challenges and may influence the interactions between biochar and the soil environment. This review explores the potential effects of biochar on the properties of calcareous soils, emphasizing its impact on physical, chemical, and biological parameters. By examining existing research on biochar applications in these soils, this paper aims to assess its viability as a sustainable soil amendment in calcareous environments. Understanding the interactions between biochar and calcareous soils is essential for establishing optimal practices for its utilization and maximizing its effectiveness in enhancing agricultural productivity and soil health in these challenging conditions.

Effect of Pyrolysis Temperature on Biochar Properties

The temperature at which biochar is produced has a significant impact on its physicochemical properties, which subsequently affect its efficacy in calcareous soils. Biochar generated at high temperatures commonly exhibits an alkaline pH. In the context of calcareous soils, this can lead to further increases in pH, potentially worsening micronutrient deficiencies. Utilizing biochars produced at lower temperatures (200–300°C) or acidified biochars may help alleviate this issue, as they tend to have a lesser impact on pH and might enhance microbial activity. High-temperature biochar can improve the retention of essential nutrients (e.g., nitrogen, phosphorus) due to its high cation exchange capacity (CEC) and surface area, which is particularly advantageous for calcareous soils that often face nutrient leaching challenges (Table 1). Khadem and Raiesi (2017) found that MBC was higher in calcareous soils amended with corn stover biochar made at 200°C compared to those treated with biochars produced at 400°C and 600°C.

Table 1: Some properties of biochar produced from different feedstocks at different pyrolysis temperature.

Feedstocks	Temperature	pH	EC (dS m^{-1})	CEC (cmol kg^{-1})	(N) (%)	(P) (g kg^{-1})	(K) (g kg^{-1})	Zn (mg kg^{-1})	Reference
Wheat straw	300°C	6.74	1.78	99	23.8	3.4	27	68	Naeem et al. (2017)
	400°C	7.80	2.15	83	19.4	3.8	33	90	
	500°C	8.00	2.60	65	18.5	4.2	41	99	
Rice straw	300°C	6.98	2.35	91	21.5	1.9	22	48	
	400°C	8.70	2.85	73	19.8	2.0	24	60	
	500°C	9.40	3.32	57	18.5	2.2	30	71	
Maize residue	200°C	6.25	3.67	18.6	-	1.9	12.4	20.1	Khadem et al. (2021)
	400°C	10.7	3.38	14.3	-	5.2	13.2	45.5	
	600°C	11.2	4.75	11.7	-	10.5	19.6	45.2	
Row corn residue	200°C	6.06	3.43	35.44	1.04	0.79	23.4	35.88	Karimi et al. 2019
	350°C	8.17	4.37	31.95	1.64	0.94	37.5	50.71	
	500°C	9.19	6.33	23.87	1.54	1.26	55.2	71.17	
Poultry manure	200°C	7.20	8.59	58	-	1.05	33.4	565	Zolfi-Bavariani et al. (2016)
	300°C	7.30	8.96	69	-	1.26	41.3	721	
	400°C	9.98	15.3	75	-	1.72	55.9	895	

Modification of Biochar

The beneficial application of biochar in calcareous soils is most effective when biochars are produced at lower temperatures, as higher pyrolysis temperatures can elevate soil pH. However, nutrient concentrations are generally higher in biochar produced at higher temperatures. The inherent variability of biochars suggests that they can be tailored for specific applications. Biochar can be modified through various processes according to its intended use (Figure 1). Biochar modified with nitric acid and/or a combination of nitric and phosphoric acids after pyrolysis enhanced the availability of nutrients, reduced soil pH and enhanced phosphorus (P) levels in both soil and plants, and promoting plant growth by positively influencing nutrient uptake (Sahin et al. 2015; Sahin et al. 2023).

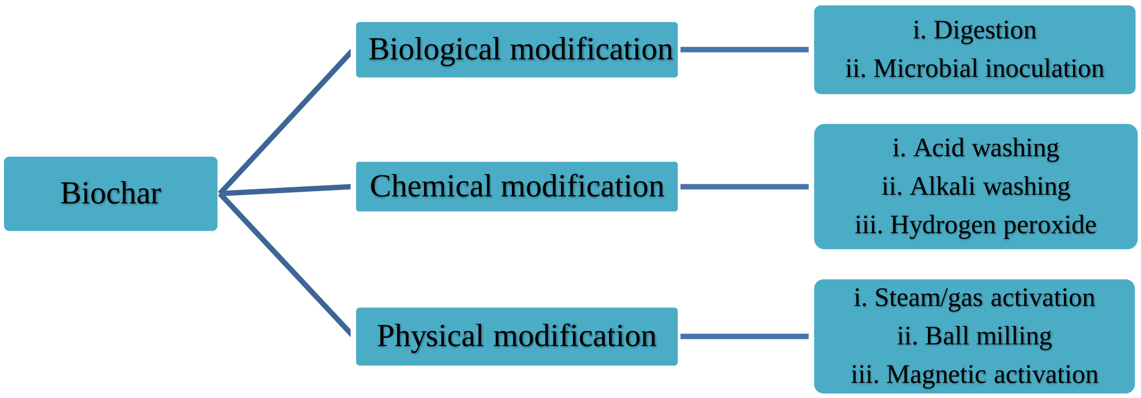


Figure 1: Schematic diagram of biochar modification techniques (Rashid et al. 2020)

Effect of Biochar on Physical Properties of Calcareous Soil

The application of biochar can have a profound impact on the physical properties of calcareous soils, which often suffer from low organic matter content, high bulk density, and poor water retention. The high surface area and porous structure of biochar provide a framework that binds soil particles together into aggregates, thereby reducing the tendency of calcareous soils to crust (Laird et al., 2010). This is particularly beneficial for densely compacted calcareous soils. Ippolito et al., (2014) reported that increasing the biochar application rate enhances the water-holding capacity of the soil-biochar mixture, a property that can be advantageous in water-limited situations (Table 2), while Amin (2018) reported that combining biochar with farmyard manure and poultry manure further improved WHC. Biochar particles create additional pore spaces within the soil matrix, lowering overall soil compaction (Mukherjee and Lal, 2015). Biochar also helps mitigate cracking through the alleviation of soil compaction, preserving tillage while reducing water evaporation, for instance, by 43% when 10% biochar was applied (Lee et al., 2022). Abdulrahman et al. (2020) found that biochar significantly increased saturated hydraulic conductivity (Ks) to 2.39–2.4 cm·hr^{-1} for treatments with biochar 4 and 8 t·ha^{-1} compared to the control at 1.36 cm·hr^{-1}.

Table 2: Biochar-amended (0, 1, 2, or 10% by wt) Portneuf soil mean (n = 4) percent gravimetric soil water content at 0, −10, −33, −100, and −300 kPa for soils incubated for 1, 6, or 12 months.

Month	Biochar application rate	Metric potential				
		0kPa	-10 kPa	-33kPa	-100kPa	-300kPa
		Gravimetric water content				
1	0	52.8 (2.1) †c‡	29.2 (0.4) c	21.4 (0.2) b	15.2 (0.1) b	11.5 (0.1) a
	1	54.5 (0.6) c	30.2 (0.2) b c	21.4 (0.1) b	15.1 (0.1) b	11.6 (0.1) a
	2	58.5 (0.5) b	30.4 (0.1) b	21.7 (0.1) b	15.4 (0.2) b	11.4 (0.0) a
	10	67.2 (0.4) a	36.0 (0.4) a	24.4 (0.2) a	16.9 (0.3) a	11.6 (0.1) a
6	0	60.2 (0.8) c	36.6 (0.4) c	28.6 (0.3) b	21.1 (0.2) b	17.5 (0.2) b
	1	61.7 (0.6) b c	38.0 (0.2) b	28.7 (0.2) b	21.2 (0.2) b	17.5 (0.3) b
	2	63.3 (0.4) b	38.5 (0.3) b	29.3 (0.2) b	21.6 (0.2) b	17.6 (0.2) ab
	10	74.0 (0.9) a	43.8 (0.6) a	32.2 (0.5) a	23.4 (0.3) a	18.3 (0.2) a
12	0	54.2 (0.6) b	37.0 (0.1) d	29.4 (0.3) c	21.3 (0.1) b	18.2 (0.8) b
	1	56.4 (0.8) b	38.6 (0.3) c	29.6 (0.2) b c	21.8 (0.2) b	17.9 (0.2) b
	2	58.4 (0.8) b	40.1 (0.2) b	30.6 (0.3) b	22.5 (0.3) ab	18.1 (0.2) b
	10	75.3 (2.9) a	52.2 (0.7) a	35.0 (0.4) a	26.0 (2.6) a	20.0 (0.3) a

† Values inside parentheses indicate 1 SEM.‡ Within a column and a given month, values followed by the same letters are not significantly different at a = 0.05 as determined using a Fisher's protected LSD

Effect of Biochar on Chemical Properties of Calcareous Soil

The introduction of biochar can significantly alter the chemical characteristics of calcareous soils, enhancing nutrient availability, cation exchange capacity (CEC), and soil pH. However, these effects are contingent on the specific properties of the biochar (e.g., feedstock, pyrolysis temperature) and the soil conditions. The acidic functional groups present on the surface of biochar produced at 200°C can counterbalance alkalinity and lead to a decrease in soil pH (Naeem et al., 2017). Additionally, the mineralization of the acidic components from biochar can lower the pH of the amended soil (Karimi et al., 2019). The numerous surface functional groups found in biochar, particularly at 200°C, along with its elevated CEC, may enhance the soil's CEC (Karimi et al., 2019; Naeem et al., 2017; Song et al. (2019) reported that the levels of soil organic carbon, total nitrogen, dissolved organic carbon, total dissolved nitrogen, and available phosphorus and potassium significantly increased with greater biochar application rates (Table 3). Amending calcareous soil with biochar notably increased soil organic matter (Amin et al., 2017).

Table 3. Physicochemical properties of the studied topsoil (0–20 cm depth) after maize harvest in October 2015 and October 2016, following application of biochar to research plots in October 2014. Values are the mean ± S.D. (n = 3).

Year	Treatment	SOC	TN	DOC	TDN	MBC	MBN
		g/kg	g/kg	mg/kg	mg/kg	mg/kg	mg/kg
October 2015	BC0	4.25 ± 0.1c	0.52 ± 0.04b	65.44 ± 1.4b	23.21 ± 0.3b	186.52 ± 16.7b	34.98 ± 1.1c
	BC2.5	5.36 ± 1.1bc	0.57 ± 0.13b	69.05 ± 7.1b	23.74 ± 0.1b	209.51 ± 14.6a	42.47 ± 4.6b
	BC7.5	6.81 ± 0.5b	0.66 ± 0.04b	72.09 ± 0.6 ab	24.70 ± 1.2a	229.12 ± 4.3a	53.19 ± 2.6a
	BC22.5	11.26 ± 1.1a	0.90 ± 0.14a	78.00 ± 3.4a	26.71 ± 1.7a	215.68 ± 7.0a	52.94 ± 2.4a
	Pr > F	**	**	*	*	*	**
October 2016	BC0	6.13 ± 0.6c	0.57 ± 0.07b	68.20 ± 2.8b	3.25 ± 0.4c	190.67 ± 11.6b	41.12 ± 4.2b
	BC2.5	6.81 ± 0.5bc	0.61 ± 0.09b	74.64 ± 2.8b	7.47 ± 1.4b	206.39 ± 11.1b	48.17 ± 2.0a
	BC7.5	7.47 ± 0.7b	0.67 ± 0.08b	85.91 ± 9.9a	10.19 ± 0.2a	234.02 ± 6.9a	48.13 ± 0.1a
	BC22.5	9.66 ± 0.9a	0.88 ± 0.04a	85.59 ± 2.0a	11.12 ± 1.6a	200.27 ± 9.0b	42.11 ± 1.0b
	Pr > F	**	**	**	**	**	*

Within columns by year, means followed by different lower-case letters between the treatments within a column are significantly different at $P < 0.05$. Abbreviations: SOC, soil organic carbon; TN, total nitrogen; DOC, dissolved organic carbon; TDN, total dissolved nitrogen; MBC, microbial biomass carbon; MBN, microbial biomass nitrogen. NS, * and ** indicate ANOVA results of $P > 0.05$, $P < 0.05$ and $P < 0.01$, respectively.

Biochar increases available phosphorus primarily by reducing the release of Ca^{2+} and Mg^{2+} through the immobilization of these metals during pyrolysis (Wang et al., 2015) and by enhancing microbial populations in biochar-treated soils (Khadem and Raiesi, 2019). The availability of P may rise when more CO_2 is released through organic matter decay and cation complexation, influenced by phosphorus fixation in calcareous soils (Motaghian et al., 2020).

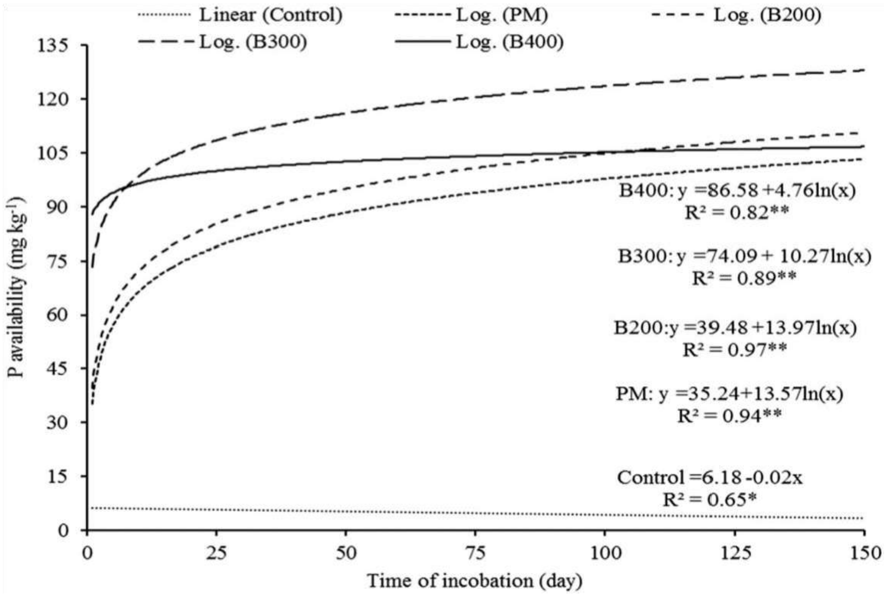


Figure 2: Soil P availability and incubation time relations in different treatments. (PM: poultry manure; B200, B300 and B400 represent biochars prepared at 200°C, 300°C and 400°C, respectively; ** and *significant at 1% and 5% levels, respectively).

Zolfi-Bavariani et al. (2016) indicated that the available P in calcareous soil treated with poultry manure was lower than in soil treated with alkaline biochar across a 1 to 150-day incubation period (Figure 2). Rasuli et al. (2022) noted that biochar increased the levels of soluble, exchangeable, non-exchangeable, and HNO_3-

extractable K due to the limited capacity of exchange sites and clay interlayers for potassium adsorption (Figure 3).

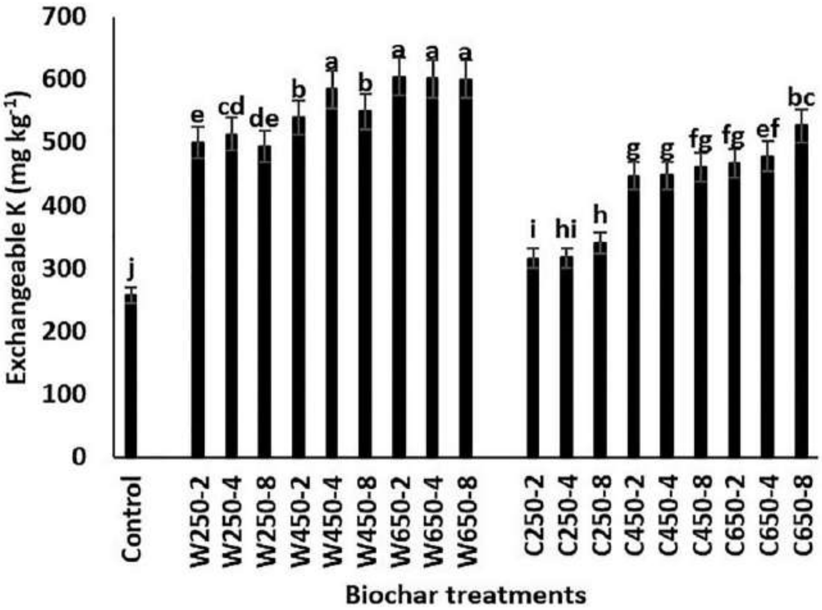


Figure 3: Exchangeable K concentration (averaged for four soils) in the experimental soils as affected by different biochar treatments. W: wheat biochar; C: corn biochar; 250, 450 and 650: pyrolysis temperature C; 2, 4 and 8: duration of pyrolysis in hours

Effect of Biochar on Biological Properties of Calcareous Soil

The biological characteristics of soil, which encompass microbial activity, enzyme activity, and biodiversity, serve as vital indicators of soil health and fertility. The responses of microbial properties, such as enzyme activity and soil respiration, to biochar application are not yet thoroughly understood and cannot be generalized across various soil types, including calcareous soils found in arid regions (Elzobair et al., 2016; Song et al., 2018). Biochar has been shown to enhance phosphatase activities (Jin et al., 2016; Khadem and Raiesi, 2019) and increase microbial populations (Nie et al., 2018). Additionally, biochar can modify mineral phosphorus fractions and boost soluble phosphorus levels in calcareous soils (Yan et al., 2018). Increases in microbial populations and phosphorus immobilization are beneficial for releasing dissolved organic carbon and altering mineral phosphorus fractions in calcareous soils (Ahmad et al., 2018). Karimi et al. (2019) found that all biochar-amended treatments resulted in a 12.2% to 67.4% increase in soil microbial biomass carbon (MBC) compared to the control treatment (Figure 4).

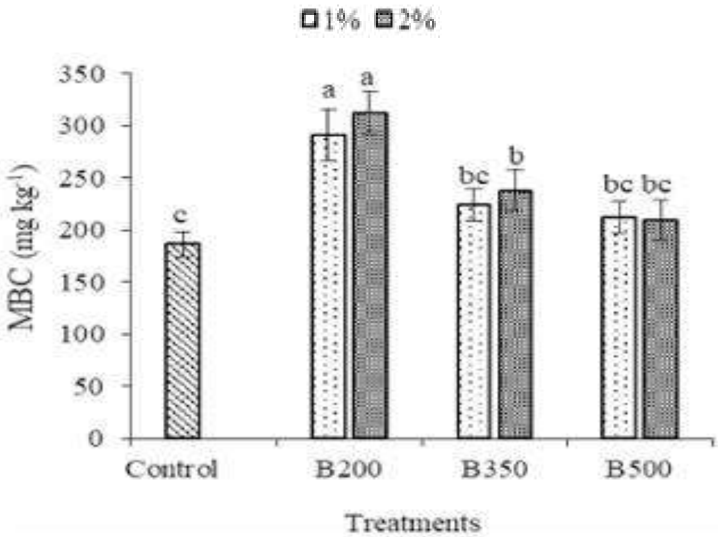


Figure 4: Microbial biomass carbon (MBC) in different biochar treatments at 1 and 2% of application rate. Different letters show the significant difference according to Duncan's test at 5% probability level (n = 3). B200, B350, and B500 corn residue biochars produced at 200 (B200), 350 (B350), and 500 (B500) °C

[Song et al. (2019)](#) reported that soil microbial biomass carbon and nitrogen (MBC and MBN) exhibited an initial increase followed by a decrease (Table 4). Biochar application also resulted in increased soil carbon content, enhanced soil respiration rates, and higher bacterial populations, while decreasing soil NO_3–N concentrations. Ippolito et al., (2014) stated that biochar rates of 2% and 10% modified the relative proportions of bacterial and fungal fatty acids, shifting the microbial community toward a greater abundance of bacteria and a reduced presence of fungi (Figure 5).

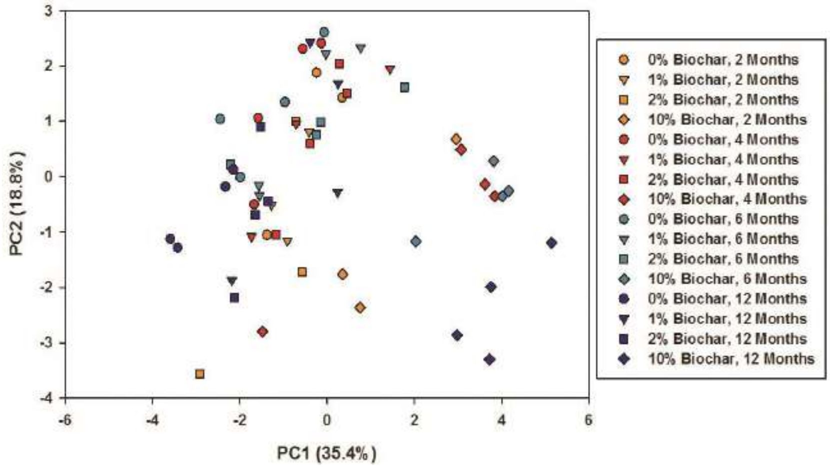


Figure 5. The effect of increasing biochar application rate (%) and time since application on soil microbial community fatty acid methyl ester profiles as determined by principal components analysis. The percent variance explained by each principal component is shown in parentheses. PC1, principal components analysis 1; PC2, principal components analysis 2.

Negative Effects of Biochar on Calcareous Soil

In contrast to the previously mentioned positive outcomes, some studies have reported negative effects associated with the sole application of biochar on soil fertility. These adverse effects include reduced bioavailability of nitrogen and phosphorus (Diatta et al., 2020; Elkhlifi et al., 2023), increased electrical conductivity, and decreased crop yields (Diatta et al., 2020; Murtaza et al., 2021). Additionally, Khadem and Raiesi (2019) reported that microbial populations in calcareous soils treated with maize residue were higher than those in soils treated with its biochar. Dume et al. (2017) noted that the application of highly alkaline biochars to calcareous soil significantly increased phosphorus sorption (Figure 6).

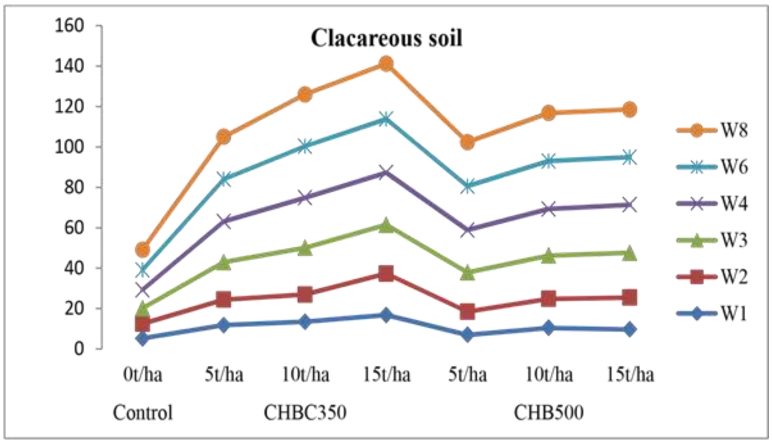


Figure 6: The effect of rate of application and incubation period of coffee husk biochar (350°C) and (500°C), on P sorption in calcareous soil

Conclusion

A comparison of the quantity of soil silicon determined at sowing and harvest shows depletion of this nutrient. The presented examples from experiments confirm the practical benefit of using the soil equivalent in processing the results of field experiments. To assess the efficacy of silicon treatment, convenient, wide-ranging, and long-term field experiments should be taken into consideration to enable plants to evolve various resistance mechanisms to deal with several adverse abiotic factors. It is recommended for soil and crop scientists to conduct extensive studies on the influence of silicon on different crops.

References

Abdulrahman, M. K., Al-Wazzan, F. A., & Al-Jawadi, L. M., 2020. Effect of polyacrylamide and biochar on calcareous soil moisture content and maize production under drip irrigation. Plant Arch, 20(2), 9505-9515.

Ahmad M, Ahmad M, El-Naggar AH, Usman AR, Abduljabbar A, Vithanage M, Elfaki J, Abdulelah AF, Al-Wabel MI., 2018. Agingeffects of organic and inorganic fertilizers on phosphorus fraction-ation in a calcareous sandy loam soil. Pedosphere 28:873–883.

Amin, A. E. E. A. Z., 2018. Amelioration of calcareous sandy soil productivity via incorporation between biochar and some organic manures. Arabian Journal of Geosciences, 11(23), 759.

Amin, A. E. E. A. Z., & Eissa, M. A., 2017. Biochar effects on nitrogen and phosphorus use efficiencies of zucchini plants grown in a calcareous sandy soil. Journal of soil science and plant nutrition, 17(4), 912-921.

Backer RGM, Schwinghamer TD, Whalen JK, Seguin P, Smith DL., 2016. Crop yield and SOC responses to biochar application were dependent on soil texture and crop type in southern Quebec, Canada. J Plant Nutr Soil Sci 176:399–408

Bolan, N., Srivastava, P., Rao, C. S., Satyanaraya, P. V., Anderson, G. C., Bolan, S., ... & Kirkham, M. B., 2023. Distribution, characteristics and management of calcareous soils. Advances in agronomy, 182, 81-130.

Diatta AA, Fike JH, Battaglia ML, Galbraith JM, Baig MB., 2020. Effects of Biochar on Soil Fertility and Crop Productivity in Arid Regions: a Review Arab J Geosci 13:1–17

Du ZL, Zhao JK, Wang YD, Zhang QZ., 2017. Biochar addition drives soil aggregation and carbon sequestration in aggregate fractions from an intensive agricultural system. J Soils Sediments 17:581–589

Dume, B., Tessema, D. A., Regassa, A., & Berecha, G., 2017. Effects of biochar on phosphorus sorption and desorption in acidic and calcareous soils. Civil and Environmental Research, 9(5), 10-20.

Elzobair KA, Stromberger ME, Ippolito JA, Lentz RD., 2016. Contrasting efects of biochar versus manure on soil microbial communities and enzyme activities in an Aridisol. Chemosphere 142:145–152

Galvez A, Sinicco T, Cayuela ML, Mingorance MD, Fornasier F, Mondini C., 2012. Short term efects of bioenergy by-products on soil C and N dynamics, nutrient availability and biochemical properties. Agric Ecosyst Environ 160:3–14

Hasanpour, I., Shirvani, M., Hajabbasi, M. A., & Majidi, M. M., 2022. Effect of acidic biochars on some chemical properties and nutrient availabilities of calcareous soils. JWSS-Isfahan University of Technology, 26(2), 39-59.

Ippolito, J. A., Stromberger, M. E., Lentz, R. D., & Dungan, R. S., 2014. Hardwood biochar influences calcareous soil physicochemical and microbiological status. Journal of environmental quality, 43(2), 681-689.

Jin Y, Liang X, Miaomiao H, Liu Y, Tian G, Shi J., 2016. Manure biochar influence upon soil properties, phosphorus distribution and phosphatase activities: a microcosm incubation study. Chemosphere 142:128–135

Karimi, A., Moezzi, A., Chorom, M., & Enayatizamir, N., 2019. Chemical fractions and availability of Zn in a calcareous soil in response to biochar amendments. Journal of Soil Science and Plant Nutrition, 19, 851-864.

Khadem, A., & Raiesi, F., 2019. Response of soil alkaline phosphatase to biochar amendments: Changes in kinetic and thermodynamic characteristics. Geoderma, 337, 44-54.

Khadem, A., Raiesi, F., Besharati, H., & Khalaj, M. A., 2021. The effects of biochar on soil nutrients status, microbial activity and carbon sequestration potential in two calcareous soils. Biochar, 3(1), 105-116.

Laird, D. A., Fleming, P., Wang, B., Horton, R., & Karlen, D. L., 2010. "Biochar Impact on Nutrient Leaching and Soil Retention of Nutrients." Soil Science Society of America Journal, 74(4), 1130-1137.

Lee, X., Yang, F., Xing, Y., Huang, Y., Xu, L., Liu, Z., ... & Zhou, H., 2022. Use of biochar to manage soil salts and water: Effects and mechanisms. Catena, 211, 106018.

Masto ER, Ansari MA, George J, Selvi VA, Ram LC., 2013. Coapplication of biochar and lignite fy ash on soil nutrients and biological parameters at diferent crop growth stages of Zea mays. Ecol Eng 58:314–322

Moradi, N., Rasouli-Sadaghiani, M. H., & Sepehr, E., 2017. Effect of biochar types and rates on some soil properties and nutrients availability in a calcareous soil. Water and Soil, 31(4), 1232-1246.

Motaghian, H., Hosseinpur, A., & Safian, M., 2020. The effects of sugarcane-derived biochar on phosphorus release characteristics in a calcareous soil. Journal of Soil Science and Plant Nutrition, 20(1), 66-74.

Mukherjee, A., & Lal, R., 2013. Biochar impacts on soil physical properties and greenhouse gas emissions. Agronomy, 3(2), 313-339.

Murtaza G, Ahmed Z, Usman M, Tariq W, Ullah Z, Shareef M, Iqbal H, Waqas M, Tariq A, Wu Y, Zhang Z., 2021. Biochar induced modifications in soil properties and its impacts on crop growth and production. J Plant Nutr 44:1677–1691

Naeem, M. A., Khalid, M., Aon, M., Abbas, G., Tahir, M., Amjad, M., ... & Akhtar, S. S., 2017. Effect of wheat and rice straw biochar produced at different temperatures on maize growth and nutrient dynamics of a calcareous soil. Archives of Agronomy and Soil Science, 63(14), 2048-2061.

Nie, S., Li, R., Xin, Y., Tan, Y.; Miao, C.; Xiang, Y.; Xiao, W., 2021. Enhanced cycling performance of Sn nanoparticles embedded into the pyrolytic biochar from tea-seed shells as composite anode materials for lithium ions batteries. Solid State Ion, 368, 115703. https://doi.org/ 10.1016/j.ssi.2021.115703.

Oliveira FR, Patel AK, Jaisi DP, Adhikari S, Lu H, Khanal SK., 2017. Environmental application of biochar: Current status and perspectives. Bioresour Technol 246:110–122

Ouyang L, Yu L, Zhang R., 2013. Efects of biochars derived from different feedstocks and pyrolysis temperatures on soil physical and hydraulic properties. J Soils Sediments 13:1561–1572

Rashid, M., Hussain, Q., Khan, K. S., Al-Wabel, M. I., Afeng, Z., Akmal, M., ... & Qayyum, M. F., 2020. Prospects of biochar in alkaline soils to mitigate climate change. Environment, climate, plant and vegetation growth, 133-149.

Rasuli, F., Owliaie, H., Najafi-Ghiri, M., & Adhami, E., 2022. Effect of biochar on potassium fractions and plant-available P, Fe, Zn, Mn and Cu concentrations of calcareous soils. Arid Land Research and Management, 36(1), 1-26.

Sahin, O., Gunes, A., Babar, S. K., Deniz, K., Kadioglu, Y. K., Ozturk, S., & Inal, A., 2023. Phosphorus-enriched rice husk biochar affected growth and mineral nutrition of wheat and its residual effects on maize production. Journal of Soil Science and Plant Nutrition, 23(3), 3085-3094.

Sahin, O., Taskin, M. B., Kaya, E. C., Atakol, O. R. H. A. N., Emir, E., Inal, A., & Gunes, A. Y. D. I. N., 2017. Effect of acid modification of biochar on nutrient availability and maize growth in a calcareous soil. Soil Use and Management, 33(3), 447-456.

Song, D., Tang, J., Xi, X., Zhang, S., Liang, G., Zhou, W., & Wang, X., 2018. Responses of soil nutrients and microbial activities to additions of maize straw biochar and chemical fertilization in a calcareous soil. European Journal of Soil Biology, 84, 1-10.

Song, D., Xi, X., Zheng, Q., Liang, G., Zhou, W., & Wang, X., 2019. Soil nutrient and microbial activity responses to two years after maize straw biochar application in a calcareous soil. Ecotoxicology and environmental safety, 180, 348-356.

Wang Y, Lin Y, Chiu PC, Imhoff PT, Guo M., 2015. Phosphorus release behaviors of poultry litter biochar as a soil amendment. Sci Total Environ 512:454–463. https://doi.org/10.1016/j. scitotenv.2015.01.093

Yan Z, Chen S, Dari B, Sihi D, Chen Q., 2018. Phosphorus transformation response to soil properties changes induced by manure application in a calcareous soil. Geoderma 322:163–171

Zolfi-Bavariani, M., Ronaghi, A., Ghasemi-Fasaei, R., & Yasrebi, J., 2016. Influence of poultry manure–derived biochars on nutrients bioavailability and chemical properties of a calcareous soil. Archives of Agronomy and Soil Science, 62(11), 1578-1591.

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

Evaluating Aloe vera's agricultural applications: Organic fertilization and sustainability

Michelle Angely MOLLEHUARA HUAYAS [1,2,*], Rıdvan KIZILKAYA [2]

[1] University of Agriculture in Krakow, Department of Soil Science and Soil Protection; Kraków, Poland
[2] Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Michelle Angely MOLLEHUARA HUAYAS
michelleangely031@gmail.com

Abstract

Aloe vera, renowned for its medicinal and cosmetic applications, has emerged as a promising candidate in sustainable agriculture due to its multifunctional properties. This review explores Aloe vera's potential as an organic fertilizer and its role in promoting environmentally friendly agricultural practices. The plant's rich chemical composition, including bioactive compounds, vitamins, and minerals, enhances its ability to improve soil fertility, stimulate microbial activity, and promote plant growth. Key applications such as foliar sprays, seed coatings, and composting have been extensively studied, revealing Aloe vera's efficacy in enhancing nutrient availability and plant productivity while reducing dependency on synthetic fertilizers. The review highlights findings from various studies that demonstrate Aloe vera's capacity to support soil health and plant development under different agricultural conditions. For instance, Aloe vera extracts have been shown to improve nutrient cycling, increase microbial diversity, and provide a sustainable alternative for crop fertilization. Moreover, Aloe vera offers additional benefits, such as mitigating abiotic stress in plants and reducing the environmental footprint of traditional farming methods. By synthesizing existing literature, this review provides a comprehensive understanding of Aloe vera's potential as a cost-effective and eco-friendly solution for modern agriculture. It also identifies key research gaps and suggests future directions for optimizing its application in large-scale farming systems. With its ability to contribute to sustainable agricultural practices, Aloe vera stands out as a valuable resource in addressing global challenges related to food security and environmental sustainability.

Keywords: Aloe Vera, Fertilizers, Plant growth, Soil dynamics

Introduction

Soil health, as defined by Doran and Zeiss (2000), refers to "the capacity of soil to function as a vital living system, within ecosystem and land use boundaries, to sustain plant and animal production, and maintain or enhance water and air quality." However, modern agricultural practices such as excessive use of chemical fertilizers, monocropping, and intensive tillage have increased soil vulnerability, leading to degradation processes such as acidification, erosion, salinization, and contamination (Tahat et al., 2020) These practices not only diminish soil quality but also reduce its capacity to sustain productivity.

Over the past decades, synthetic fertilizers have played a significant role in increasing crop yields due to their impact on plant nutrition. However, their widespread use has come at a cost. The excessive application of chemical fertilizers has led to soil degradation and the accumulation of residual chemicals in plant tissues, posing risks to human and animal health (Nuri Salem, 2021). As a result, there is a growing global emphasis on sustainability and eco-friendly agricultural practices that address environmental concerns while also being socially and economically viable.

Organic fertilizers are an effective alternative, as they promote healthier soils by enhancing nutrient-rich organic matter and supporting beneficial microbial activity (Kiełbasa et al., 2018) Among the various organic resources, Aloe vera (syn.: *Aloe barbadensis Miller*), a member of the Asphodelaceae family, stands out for its potential in agriculture. Native to the arid regions of North Africa, Aloe vera has been utilized for centuries in agriculture, cosmetics, and medicine (Martínez-Burgos et al., 2022). Its adaptability to hot and dry climates has made it a widely cultivated crop across the globe. Research indicates that Aloe vera contributes to seed germination, vegetative growth, and crop quality by enhancing plant tolerance to pathogens and improving overall productivity (Goolmohammadi, 2022).

The main objective of this review is to explore the potential of Aloe vera as an organic fertilizer, focusing on its ability to promote vegetative growth in plants and improve soil dynamics. This study aims to offer a sustainable and eco-friendly alternative to traditional chemical fertilizers, addressing the challenges of modern agriculture (Efterpi V. Christaki & Pagiota C. Florou-Pan, 2010).

Ideal Growing Conditions and Chemical Profile of Aloe vera

Ideal Growing Conditions

Aloe vera is a highly adaptable plant that thrives under various environmental conditions. According to Deshmukh et al. (2023), it grows best in sandy, well-drained soils with a slightly acidic to neutral pH (6.0–7.0), such as sandy or loamy soils. Aloe vera can tolerate slightly saline soils and develops optimally at temperatures between 20°C and 30°C, with a minimum temperature of 5°C, below which plant damage can occur. The ideal annual rainfall for its growth ranges from 500 to 1000 mm.

Chemical Composition of Aloe vera

Aloe vera consists of two primary sections: the external green rind, containing vascular bundles, and the inner colorless parenchyma that holds the aloe gel. The gel is highly hydrous, with approximately 98.5% water content and a pH of 4.5. The solid fraction, comprising 0.5–1% of its mass, contains various bioactive compounds, including vitamins, enzymes, and polysaccharides (Di Scala et al. 2013; Raksha, 2014). These compounds contribute significantly to soil fertility and plant health (Table 1).

Table 1. Chemical Compounds of Aloe vera and Their Role in Soil and Plant Health (Martínez-Burgos et al., 2022; Peterson Daniel and Daniel, 2024).

Category	Description	Contribution
Polysaccharides	Includes glucomannan and acemannan, retaining water and improving soil structure	Enhances soil moisture, reduces compaction, and supports root growth in drought-prone soils
Sugars	Mannose-6-phosphate, glucose, fructose	Provides energy for cells, stimulates beneficial microbial activity
Enzymes	Amylase, alkaline phosphatase, catalase, lipase, carboxypeptidase, cyclooxidase.	Releases nutrients to support microbial activity and nutrient cycling
Vitamins	A, B1, B2, B3 B6, B12, C, E, folic acid (B9), β-carotene, α-tocopherol	Facilitates nitrogen metabolism and amino acid synthesis
Minerals	Ca, K, P, Mg, Zn, etc.	Improves photosynthesis, cell wall strength, and stress adaptation
Amino Acids	Alanine, arginine, arginine, glycine, histidine, hydroxyproline, lysine, proline, tyrosine.	Enhances plant resilience to environmental stress
Antimicrobial Compounds	Phenolic compounds, salicylic acid	Improves plant defense mechanisms and provides antioxidant properties

Agricultural Application Methods of Aloe Vera

Foliar Application of Aloe vera Extracts

Foliar spraying is a widely studied method to apply Aloe vera extracts directly to plants through a spray bottle. In recent research, Tucuch-Haas CJ et al. (2022), demonstrated that foliar application of diluted Aloe vera gel improved root development in pepper seedlings (Capsicum chinense). The application increased fresh biomass by 18%, stem diameter by 11%, and leaf number by 13%, showcasing its effectiveness in enhancing plant growth and overall quality. Similarly, Abbas et al. (2016), analyzed the effect of Aloe vera leaf extract on Salvia officinalis L. under sandy soils. The study showed significant improvements in plant height, biomass, and leaf thickness, highlighting its potential to replace synthetic fertilizers in certain conditions.

Incorporating Aloe vera into Compost and Organic Fertilizers

Composting is a natural process where organic materials decompose into stabilized forms, enhancing soil structure and nutrient availability. Aloe vera, when integrated into compost, enriches soil organic matter and improves cation exchange capacity (CEC). Khater et al. (2020), demonstrated that combining farmyard manure with Aloe vera extract enhanced vegetative growth parameters in Carum carvi L., including plant height and biomass. Aloe vera's role in stimulating seed germination and improving soil moisture retention makes it a valuable additive for compost.

Another notable study by Nejatzadeh (2024), examined the effect of Aloe vera in bio-compost preparation. Aloe vera not only accelerated the decomposition process but also enriched the compost with key nutrients such as nitrogen (N), phosphorus (P), and potassium (K). This nutrient-enriched compost improved seed germination rates and root development in Phaseolus vulgaris (common bean). Aloe vera's gel and leaf residues contributed to microbial proliferation, enhancing the breakdown of organic matter and producing a more stable compost.

Seed Soaking and Coating with Aloe vera Gel

Seed Soaking

Seed soaking is a pre-sowing technique where seeds are immersed in a solution to hydrate them and activate germination enzymes. This method facilitates faster and more uniform germination by allowing the seeds to absorb water and beneficial compounds. Aloe vera gel, known for its rich bioactive composition, is increasingly being explored as a natural substitute for chemical seed treatments. René et al. (2024), evaluated the efficacy of Aloe vera gel for tomato seeds, reporting enhanced plant height growth and an increased number of leaves. The study highlighted that Aloe vera gel, when combined with soil, accelerates the germination process, improving the early establishment of tomato plants.

The use of Aloe vera gel in seed soaking offers several advantages:

• Rich Nutrient Composition: Aloe vera provides essential nutrients, vitamins, and bioactive compounds that stimulate enzyme activity, supporting faster seed germination.

• Stress Resistance: The gel's antioxidant and antimicrobial properties protect seeds from abiotic and biotic stress during germination.

Seed Coating

Seed coating involves applying a thin, protective layer around seeds, which can include nutrients, protective compounds, and beneficial microorganisms. Aloe vera gel is particularly effective in this regard due to its antimicrobial properties and compatibility with biofertilizers. Javed et al. (2022), demonstrated the integration of rhizobia and mycorrhizal fungi with Aloe vera-coated seeds, facilitating symbiotic relationships that enhance biological nitrogen fixation in leguminous plants.

Yıldırım (2020), investigated the impact of Aloe vera coating on wheat seeds under varying water availability. The study found that Aloe vera-coated seeds delayed germination in dry conditions, preventing premature sprouting and ensuring better survival rates in arid environments. Additionally, Aloe vera coatings improved seed viability and adaptability by providing a moisture-retentive barrier.

Key benefits of Aloe vera seed coatings include:

• Protection Against Pathogens: Phenolic compounds and salicylic acid in Aloe vera create a barrier against fungal pathogens and insect pests.

• Enhanced Nutrient Uptake: The gel facilitates the absorption of nutrients and water, promoting healthier seedlings.

• Sustainability: Aloe vera serves as a cost-effective and eco-friendly alternative to synthetic seed coatings, reducing environmental risks.

These methods demonstrate the versatility of Aloe vera in seed treatments, offering sustainable and effective solutions to improve germination rates, seedling vigor, and overall crop resilience.

Conclusion

In conclusion, Aloe vera gel, enriched with a wide range of bioactive compounds, has demonstrated significant potential in enhancing plant growth and improving soil health. As one of the most versatile and eco-friendly resources, Aloe vera aligns with global sustainability goals by offering a viable alternative to traditional chemical fertilizers. Its applications in foliar sprays, compost mixtures, and seed treatments not only improve crop productivity but also support soil structure, nutrient cycling, and microbial activity.

This review highlights that Aloe vera-based solutions can reduce dependency on synthetic inputs, mitigate soil degradation, and contribute to sustainable agricultural practices. However, to fully realize its potential, future research should focus on:

• Standardizing application methods for various crops and soil types.

• Determining optimal concentrations and formulations to maximize its efficacy under diverse environmental conditions.

• Conducting large-scale trials to evaluate its long-term impact on crop yield and soil quality.

• Exploring its integration with other sustainable practices, such as biofertilizers and organic amendments.

By addressing these gaps, Aloe vera can be effectively scaled up for broader agricultural use, providing farmers with a cost-effective, sustainable, and environmentally friendly alternative. This versatile plant holds the promise of transforming modern agriculture while preserving ecological balance and ensuring food security for future generations.

References

Abbas, S., Zaglool, M., El-Ghadban, E., Abd El-Kareem, S., Waly, A., 2016. Effect of foliar application with aloe leaf extract (ALE) on vegetative growth, oil percentage and anatomical leaf structure of sage (Salvia officinalis L.) plant under sand soil conditions. *Hortscience Journal of Suez Canal University* 5, 9–14. https://doi.org/10.21608/hjsc.2016.6401

Deshmukh, Nandakishor Bhaurao, Taware, T.J., Lokde, S.K., Chude, G.D., Deshmukh, Nandkishor B, 2023. A Review on Aloe Vera Used For Socioeconomic Empowerment Shraddha institute of pharmacy kondala zambre washim. *International Journal of Pharmaceutical Research and Applications* 8, 1179–1181.

Di Scala, K., Vega-Gálvez, A., Ah-Hen, K., Nuñez-Mancilla, Y., Tabilo-Munizaga, G., Pérez-Won, M., Giovagnoli, C., 2013. Chemical and physical properties of aloe vera (Aloe barbadensis Miller) gel stored after high hydrostatic pressure processing. *Food Science and Technology* 33, 52–59.

Efterpi V. Christaki, Pagiota C. Florou-Pan, 2010. Aloe vera: A plant for many uses. *Journal of Food, Agriculture & Environment* 8(2), 1–5.

Goolmohammadi, F., 2022. Medical plant of Aloe Vera in desert regions of Iran: Greenhouses, economic importance, development, extension, processing and marketing. *Black Sea Journal of Agriculture* 5, 1–15.

Javed, T., Afzal, I., Shabbir, R., Ikram, K., Saqlain Zaheer, M., Faheem, M., Haider Ali, H., Iqbal, J., 2022. Seed coating technology: An innovative and sustainable approach for improving seed quality and crop performance. *Journal of the Saudi Society of Agricultural Sciences* 22, 536-545. https://doi.org/10.1016/j.jssas.2022.03.003

Kiełbasa, B., Pietrzak, S., Ulén, B., Drangert, J.O., Tonderski, K., 2018. Sustainable agriculture: The study on farmers' perception and practices regarding nutrient management and limiting losses. *Journal of Water and Land Development* 36, 67–75. https://doi.org/10.2478/jwld-2018-0007

Martínez-Burgos, W.J., Serra, J.L., MarsigliaF, R.M., Montoya, P., Sarmiento-Vásquez, Z., Marin, O., Gallego-Cartagena, E., Paternina-Arboleda, C.D., 2022. Aloe vera: From ancient knowledge to the patent and innovation landscape – A review. *South African Journal of Botany* 147, 993–1006. https://doi.org/10.1016/j.sajb.2022.02.034

Tahat, M.M., Alananbeh, M.K., Othman, A.Y., Leskovar, I.D., 2020. Soil Health and Sustainable Agriculture. Sustainability 12(12), 4859. https://doi.org/10.3390/su12124859

Nejatzadeh, F., 2024. Effect of Vermicompost and Nitrogen Fertilizer on the Growth and Production of Aloe Vera. *International Journal of Plant & Soil Science* 36 (4): 337-345. https://doi.org/10.9734/ijpss/2024/v36i44486

René, N.P., Charlotte, T.D., Faustin, S.D., Francis, S.E., Désiré, N.K., Selastique, A.D., 2024. View of influence of Aloe Vera gel on germination and early growth of tomato (Solanum lycopersicum) seedlings in the nursery. *Journal of Experimental Agriculture International* 46, 91-102. https://doi.org/10.9734/jeai/2024/v46i102928

Nuri Salem, A., 2021. Use of fertilizers or importance of fertilizers in agriculture. International Journal of Advanced Academic Studies 3, 52–57.

Peterson Daniel, C., Daniel, C.P., 2024. Potential health benefits of Aloe vera in livestock: A Review. *Journal of Applied Veterinary Sciences* 9, 94–104. https://dx.doi.org/10.21608/javs.2023.243964.1287

Raksha, B., 2014. Bioactive compounds and medicinal properties of Aloe Vera L.: An update. *Journal of Plant Sciences* 2, 102-107. https://doi.org/10.11648/j.jps.20140203.11

Khater, R.M., Abd-Allah, W.H.A., El Shafay, R.M.M., 2020. Effect of organic fertilization and spraying Aloe Vera extract on the growth and productivity of Carum Carvi L. plant under shalateen conditions In Egypt. *Journal of Agriculture, Food and Ecology* 20, 4951–4972.

Tucuch-Haas, C.J., Cen-Caamal, J.C., Kancab-Uc, R.A., Tucuch-Haas, J.I., 2022. Uso de gel de Aloe vera en la producción de plántulas de Capsicum chinense. *Biotecnia* 24, 116-121. https://doi.org/10.18633/biotecnia.v24i1.1542

Yildirim, M., 2020. Effects of Coating Treatment with Aloe Vera and Glycerol on germination delay and seed viability of wheat under different water levels. *Kahramanmaraş Sütçü İmam Üniversitesi Tarım ve Doğa Dergisi* 23, 994–1004. https://doi.org/10.18016/ksutarimdoga.vi.688270

Impact of climate change on soil water balance in agricultural systems

Muhammad Haseeb SHOUKAT *, Michał GĄSIOREK
University of Agriculture Krakow, Department of Soil Science and Agrophysics, Krakow, Poland

***Corresponding Author**

Muhammad Haseeb SHOUKAT
Haseebawan065@gmail.com

Abstract

Dynamics of Soil water balance has increasingly altered because of Climate Change and its Influence on Agricultural productivity worldwide. Because variations in the temperature and precipitation patterns and extreme weather events like floods and droughts affect the soil water balance with implication for yield of crops, soil health and water resources management. In this paper I examine the direct and indirect climate change impact on soil water balance and explore adaptation strategies for sustainable agriculture management and identify areas for research.

Keywords: Precipitation Patterns, Soil Health, Adaptive strategies, Crop Productivity, Floods

Introduction

Soil water balance plays an important role in agriculture as it identifies the availability of water for crops, affects nutrients cycle and contribute to soil health. Climate Change process these factors which create incredible challenges for global agricultural system. Increase in temperature changes the pattern of precipitation and create problematic events like droughts and floods (IPCC, 2021). Knowledge of these factors is very key for the develop of adaptive agricultural practices that focus on water availability and crop resilience.

Effects of Climate Change on Soil Water Balance

Temperature Increases and Evapotranspiration

Evapotranspiration accelerates when temperature increases which increase the water loss from soil and water stress in agriculture intensifies. Higher evapotranspiration rates decrease soil moisture, necessitating increased irrigation to meet crop needs (Allen et al., 2015). Additionally, studies have shown that temperature-induced evapotranspiration is a major factor in declining soil moisture, leading to reduced water availability for crops and increased vulnerability to drought (Lobell et al., 2011; Trenberth et al., 2014).

Changes in Precipitation Patterns

Precipitation patterns has been changed and effected a lot globally by Climate Change, which makes rainfall very intense but less frequent. Because of this reason the runoff increases and soil infiltration, while prolonged dry periods limit soil moisture recharge, affecting root-zone water availability (Pereira et al., 2018). Research also indicates that altered precipitation patterns contribute to spatial and temporal variability in soil moisture, impacting crop growth and productivity (Allen et al., 2010; Knox et al., 2012).

Extreme Weather Events: Droughts and Floods

Because of Climate Change the frequency of extreme events also increases such as droughts and floods. Droughts became the reason of soil desiccation, while water saturation and nutrient leaching happened because of floods, both affecting soil fertility and crop yield incredibly (Schiermeier, 2011). Moreover, extreme events can lead to long-term degradation of soil structure, reducing its capacity to retain water and support plant growth (Blanco & Lal, 2008; Rosenzweig et al., 2014).

Impacts on Agricultural Systems

Crop Yield and Productivity

Crop yield reduce significantly because of climate induced soil moisture imbalance and water stress during growth stages. Productivity also affects because of less water availability and increased water demand for plant growth (Rodrigues & Pereira, 2009). Studies have highlighted that climate variability, especially prolonged droughts, results in substantial yield reductions for major crops such as wheat, maize, and rice (Fischer et al., 2014; Lobell & Gourdji, 2012).

Soil Health and Nutrient Cycling

Moisture levels is very important for soil health which influence nutrient cycling. Organic matter composition increases because of dry condition due to climate change, while excessive moisture causes nutrient leaching, degrading soil quality (Lal, 2016). Furthermore, fluctuations in soil moisture have been linked to changes in microbial activity, which are critical for nutrient availability and soil fertility (Bardgett & van der Putten, 2014; Rustad et al., 2001).

Adaptation Strategies for Sustainable Water Management

Improved Irrigation Systems

Efficient irrigation, like drip and sprinkler systems, helps reduce water loss, ensuring soil moisture for crops even in dry conditions. These methods conserve water by delivering it directly to the root zones, reducing evaporation losses (Fereres & Soriano, 2007). Additionally, precision irrigation techniques using sensors and remote sensing can further optimize water use efficiency in agriculture (Sadler et al., 2005; Evans & Sadler, 2008).

Conservation Tillage and Soil Covering

Mulching and conservation tillage reduce evaporation, improve water retention and protect soil structure. Cover crop is also one of the ways which help to retain moisture and reduce soil erosion and stabilizing soil water balance in climates prone to variability (Hobbs et al., 2008). Studies also suggest that conservation tillage can enhance carbon sequestration, which improves soil structure and water-holding capacity (Six et al., 2000; Lal, 2004).

Soil Amendments and Organic Matter Management

Compost and Biochar are the type of amendments which improve soil structure and water retention capacity, enhancing resilience against dry and heavy rainfall. These amendments also support soil fertility and health, crucial for sustainable farming (Liang et al., 2006). Recent studies have demonstrated that biochar can significantly enhance soil moisture retention and improve plant water-use efficiency under drought conditions (Jeffery et al., 2015; Lehmann et al., 2011).

Future Research Directions

Research into climate-resilient soil management practices, especially for rain-fed agricultural systems, is needed. Further studies could focus on developing drought-resistant crop varieties, enhancing soil moisture prediction models, and investigating region-specific adaptation techniques (Lal et al., 2017). Additionally, research on the integration of climate-smart technologies and digital tools in soil water management could provide new solutions for adapting to changing climate conditions (Challinor et al., 2014; Campbell et al., 2016). Moreover, precision agricultural tools like remote sensing and soil moisture sensors uses could enable more efficient water management by providing real-time data to optimize irrigation schedules and detect early signs of water stress in crops. By combining traditional knowledge with modern technologies, these integrated solutions could provide a comprehensive framework for managing soil and water resources in the face of climate change.

Conclusion

Climate Change is very dangerous to soil water balance in agriculture system, which is going to affect crop yield, productivity and soil health. So, to deal with this problem adaptive water managements practices are very important. Also, it's important to do research on adaptation strategies, soil amendments Also its important to do research on adaptation strategies, soil amendments and effective irrigation practices such as drip and sprinkler irrigation will be essential for future of agricultural sustainability in the face of Climate Change. These methods can help optimize water usage, reduce waste, and improve soil moisture retention, ensuring that crops continue to thrive under changing climatic conditions. Long-term solutions can also be found by incorporating climate-resilient crops, enhancing soil structure with organic amendments, and encouraging water-efficient farming practices. We can lessen the adverse effects of climate change on agriculture and transition to more resilient and sustainable farming systems by concentrating on these adaptation techniques and regularly observing soil and water dynamics.

References

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao, Rome, 300(9), D05109.

Bindoff, N. L., Stott, P. A., AchutaRao, K. M., Allen, M. R., Gillett, N., Gutzler, D., ... & Zhang, R. (2014). Detection and attribution of climate change: from global to regional. Climate change 2013: the physical science basis.

Bardgett, R. D., & Van Der Putten, W. H. (2014). Belowground biodiversity and ecosystem functioning. Nature, 515(7528), 505-511.

Blanco, H., & Lal, R. (2008). Principles of Soil Conservation and Management. Springer.

Campbell, B. M., Thornton, P., Zougmoré, R., van Asten, P., & Lipper, L. (2016). Sustainable intensification: What is its role in climate-smart agriculture? Current Opinion in Environmental Sustainability, 8, 39-43.

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. Nature Climate Change, 4(4), 287-291.

Evans, R. G., & Sadler, E. J. (2008). Methods and technologies to improve efficiency of water use. Water Resources Research, 44(7).

Fereres, E., & Soriano, M. A. (2007). Deficit irrigation for reducing agricultural water use. Journal of Experimental Botany, 58(2), 147-159.

Fischer, G., Shah, M., Tubiello, F. N., & van Velthuizen, H. (2014). Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990-2080. Philosophical Transactions of the Royal Society B: Biological Sciences, 360(1463), 2067-2083.

Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences, 363(1491), 543-555.

IPCC. (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jeffery, S., Verheijen, F. G., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agriculture, ecosystems & environment, 144(1), 175-187.

Knox, J. W., Hess, T. M., Daccache, A., & Wheeler, T. R. (2012). Climate change impacts on crop productivity in Africa and South Asia. Environmental Research Letters, 7(3), 034032.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. Science, 304(5677), 1623-1627.

Lal, R. (2016). Enhancing ecosystem services with no-till. Renewable Agriculture and Food Systems, 31(2), 99-105.

Lal, R. (2020). Managing soil water to improve crop productivity and environmental quality. Advances in Agronomy, 167, 1-28.

Lal, R., Delgado, J. A., Groffman, P. M., Millar, N., Dell, C., & Rotz, A. (2017). Management to mitigate and adapt to climate change. Journal of Soil and Water Conservation, 66(4), 276-285.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota – A review. Soil Biology and Biochemistry, 43(9), 1812-1836.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., & Skjemstad, J. O. (2006). Black carbon increases cation exchange capacity in soils. Soil Science Society of America Journal, 70(5), 1719-1730.

Lobell, D. B., & Gourdji, S. M. (2012). The influence of climate change on global crop productivity. Plant Physiology, 160(4), 1686-1697.

Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. Science, 333(6042), 616-620.

Pereira, L. S., Cordery, I., & Iacovides, I. (2018). Coping with Water Scarcity: Addressing the Challenges. Springer.

Rodrigues, G. C., & Pereira, L. S. (2009). Assessing economic impacts of deficit irrigation as related to water productivity and water costs. Biosystems Engineering, 103(4), 536-551.

Rosenzweig, C., Iglesias, A., Yang, X. B., Epstein, P. R., & Chivian, E. (2014). Climate change and extreme weather events; implications for food production, plant diseases, and pests. Global Change & Human Health, 2(2), 90-104.

Rustad, L. E., Campbell, J. L., Marion, G. M., Norby, R. J., Mitchell, M. J., Hartley, A. E., ... & Gholz, H. L. (2001). A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. Oecologia, 126(4), 543-562.

Sadler, E. J., Camp, C. R., & Evans, R. G. (2007). New and future technology. Irrigation of agricultural crops, 30, 607-626.

Schiermeier, Q. (2011). Increased flood risk linked to global warming. Nature, 470.

Six, J., Feller, C., Denef, K., Ogle, S. M., de Moraes Sa, J. C., & Albrecht, A. (2000). Soil organic matter, biota and aggregation in temperate and tropical soils - Effects of no-tillage. Agronomie, 20(7), 755-775.

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

Determination of risk levels of some heavy metals in Menemen Plain

Murat Cagatay KECECI [1,*], Levent ATATANIR [2]

[1] Black Sea Agricultural Research Institute, Department of Soil and Water Resources, Samsun, Türkiye
[2] Aydin Adnan Menderes University, Faculty of Agriculture, Department of Soil Science and Soil Nutrition, Aydın, Türkiye

***Corresponding Author**

Murat Cagatay KECECİ

muratcagatay.kececi@tarimorman.gov.tr

Abstract

The risk of heavy metal contamination in agricultural areas has gained significant importance over the years due to its harmful effects on food safety and the environment. The aim of this study is to determine the status of heavy metal accumulation in the Menemen Plain within the borders of Izmir province and to assess the future risk using the enrichment factor and geoaccumulation index. For this purpose, a total of 552 soil samples were collected from 138 points at depths of 0–20, 20–40, 40–60, and 60–90 cm, and the risk levels were analyzed. When the enrichment factors of chromium (Cr) and lead (Pb) were examined, they were found to range between 0.42 and 3.07 for chromium and between 0.82 and 3.53 for lead. While low to moderately low risk levels were generally observed on the surface, the risk decreased to low or negligible levels with increasing depth. For nickel (Ni), the enrichment factor ranged between 1.20 and 3.49, indicating low to moderate risk across all depths. According to the results of the geoaccumulation index calculations, almost no risk was observed for chromium and lead, whereas a low level of risk was determined for nickel in all layers. The surface and near-surface risks are attributed to environmental factors such as agricultural and industrial activities, given the region's proximity to industrial zones, urban areas, and farmland. The risks detected in deeper layers are likely due to the parent material of the soil.

Keywords: Heavy metal contamination, enrichment factor, geoaccumulation index, Menemen Plain

Introduction

The increase in industry, urbanization and agricultural activities from year to year has made environmental pollution a global problem. Heavy metals such as chromium (Cr), lead (Pb) and nickel (Ni) pose a danger to natural ecosystems and human health due to their permanent structures and accumulation potential in the environment. The accumulation of these metals in soil and water resources causes decreases in plant production, reduces agricultural productivity and can harm living health through the food chain (Kabata-Pendias and Pendias, 2001; Alloway, 2013; Wuana and Okieimen, 2011). Heavy metals such as Pb, Ni and Cr cause significant pollution problems in the environment because of both natural processes and anthropogenic activities.

Lead is usually released into the environment from mining, battery production, paint and fuel use. Its accumulation in the soil can pass into the food chain and cause neurotoxic effects on human health. It can negatively affect the development of the nervous system, especially in children, and cause learning disabilities and IQ loss. In some agricultural areas in India, lead levels in the soil have been reported to exceed the safe limit of 100 mg/kg (Gupta et al., 2021). On the other hand, long-term accumulation of nickel can lead to health problems such as skin allergies, respiratory diseases and cancer. Nickel concentrations in agricultural lands in Europe have been reported to range between 40-60 mg/kg, posing a risk to both agriculture and human health (Smith and Jones, 2022). Chromium, especially from the leather processing, metal plating and paint industries, is highly toxic and has carcinogenic properties in the hexavalent form of chromium. In countries such as the USA and China, chromium levels in soils in industrial areas have been found to exceed 200 mg/kg, posing serious ecological and health risks (Chen et al., 2021). Assessment of the accumulation status of heavy metals and the risks they may pose in the future is a critical requirement for ecosystem health. Enrichment factor (EF) and geoaccumulation index (Igeo) are the main methods used to assess the potential of heavy metal pollution to pose a risk for the future. Determining the natural and anthropogenic accumulation rates of elements is of great importance in predicting future risks in sensitive environments such as agricultural areas and water resources (Sutherland, 2000; Wuana and Okieimen, 2011; Alloway, 2013). Studies by Sutherland (2000) and Müller (1969) have shown that the enrichment factor is quite effective in assessing anthropogenic effects by comparing metal levels in soil samples with natural contents. The geoaccumulation index is accepted as an important tool in determining the degree of environmental pollution by providing the opportunity to compare the accumulation levels of heavy metals with the pre-industrial period.

This study aims to determine the Cr, Pb and Ni accumulations in the Seyrek and Kesik Secondaries Irrigation areas of Menemen Plain in Izmir province and to conduct risk analysis using the enrichment factor and geoaccumulation index. This study also aims to contribute to environmental management and protection strategies by providing a comprehensive assessment of the source, extent and future risk status of heavy metal pollution.

Material and Methods

The research was conducted in the Kesik and Seyrek secondary irrigation areas, which are the two largest irrigation areas of the Menemen Plain located in the last part of the Gediz basin (Figure 1). The Seyrek secondary irrigation area, located in the southwestern part of the Menemen Plain, starts from Menemen and extends along the Seyrek-Süzbeyli line and empties into the Aegean Sea from the east of İzmir Bird Paradise. The Kesik secondary irrigation area is located just north of the Seyrek secondary irrigation area and starts from Menemen and extends to the İzmir Free Zone. The total length of the Kesik and Seyrek secondary areas is about 30 km and the total area they cover as irrigation areas is 91.1 km^2.

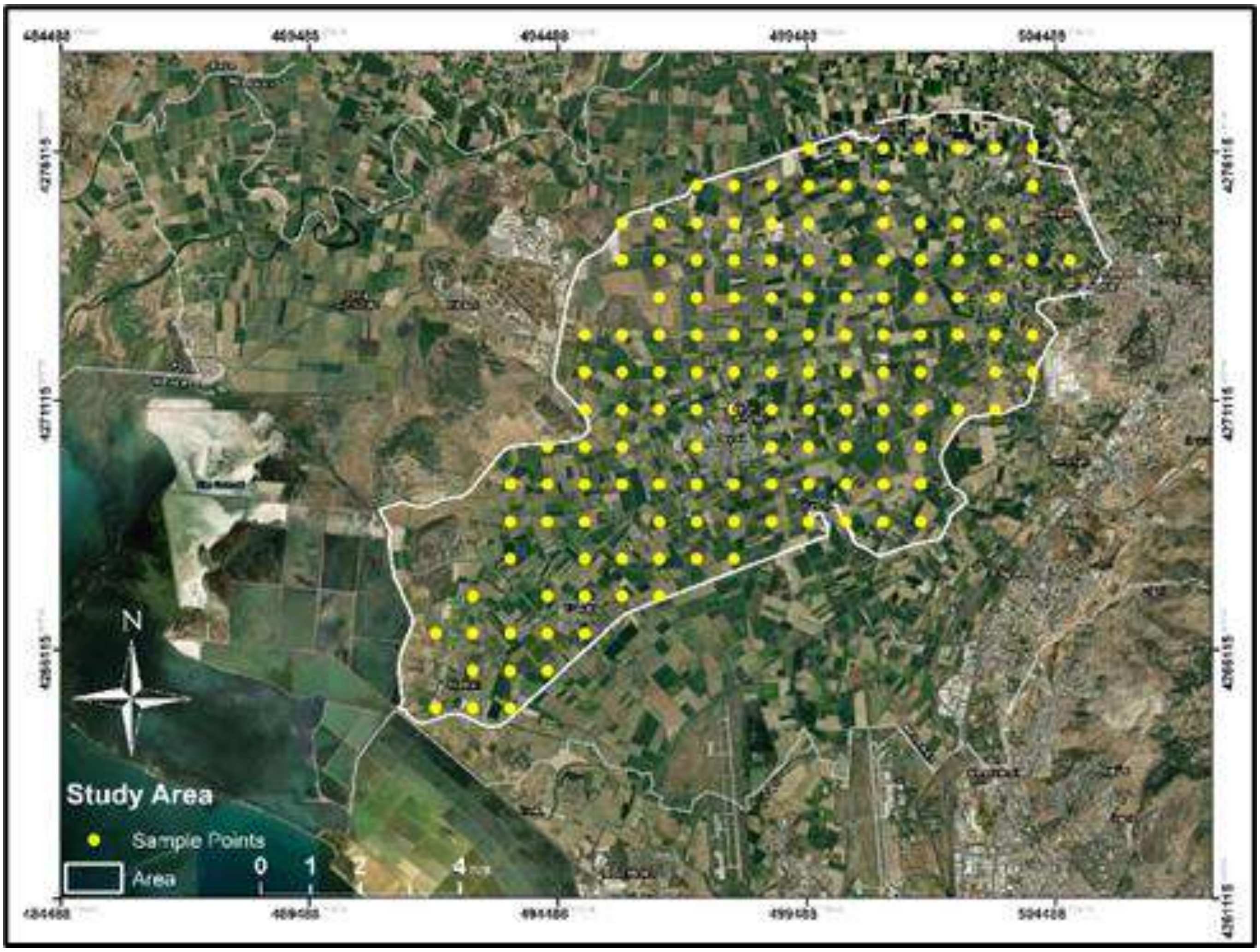


Figure 1. Study area and soil sample points

The Menemen Plain has a climate type with hot and dry summers and mild and rainy winters (Özden et al., 2009). The long-term average precipitation of the region is 540 mm, 50.07% of the precipitation occurs in winter, 24.63% in spring, 2.11% in summer and 23.19% in autumn. The average temperature of the plain is 16.9 ºC, the lowest average temperature in January was reported as -7.6 ºC and the highest average temperature in August was reported as 44.3 ºC (Table 1). The average humidity rate varies between 48.3% and 70.9% (UTAEM, 2024). The Menemen Plain soils consist of alluvial deposits formed over time by the Gediz River and its tributary streams and the soils developed on these deposits (Tepecik et al., 2022). According to previous research, the majority of the Menemen Plain soils have the texture of clay loam, sandy loam, loam and silty loam, and the majority of the soils have medium and medium-heavy textures (Özden et al., 2019).

Table 1. Long-term (1954-2023) average monthly meteorological data of the research area

1954-2023	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Agu**	**Sept**	**Oct**	**Nov**	**Dec**	**Average Yearly**
Av Temp (^{0}C)	7.8	8.8	11.0	15.0	20.0	24.7	27.0	26.4	22.3	17.4	12.9	9.7	16.9
Max Temp (^{0}C)	22.8	26.5	31.9	33.8	40.2	43.0	42.3	44.3	41.4	39.4	31.3	25.4	44.3
Min Temp (^{0}C)	-7.6	-5.6	-4.4	-1.4	2.8	6.7	10.7	10.8	6.0	1.2	-2.0	-4.5	-7.6
Humidity (%)	69.7	67.7	63.9	60.7	57.3	52.7	48.3	51.3	56.4	63.5	67.2	70.9	58.0
Prep (mm)	90.1	74.2	61.4	42.3	27.2	6.7	2.4	2.7	12.5	37.3	74.4	108.3	540.0

In this study, in order to conduct heavy metal risk analysis, a total of 552 soil samples were taken from 138 points at 4 depths (0-20 cm, 20-40 cm, 40-60 cm and 60-90 cm) in the research area divided into 1 km grids in the Geographic Information System (GIS) environment (Figure 1). In these samples, nickel, chromium and lead laboratory analyze were carried out according to the ICP-OES method and the obtained analysis results were evaluated using the enrichment factor and geoaccumulation index. In this evaluation, the formulas (1) and (2) given below and specified by Cemek and Kızılkaya (2006) and Bayraklı and Dengiz (2020) were used to make the calculations.

(1) EF = (Heavy MetalSoil) / (Heavy MetalBackground)

(2) $Igeo = Log_2[Csi / (1.5 \times Cbi)]$

In the EF equation given above (1); Heavy metalSoil is total heavy metal concentration in soil sample and heavy metalBackground is the average heavy metal concentration of the Earth's crust. This value was accepted as 100 for Cr, 80 for Ni, and 14 for Pb. In Igeo equation (2); Csi is the metal concentration in the soil sample and Cbi is the background value of this metal (Bayraklı and Dengiz, 2020). The coefficient "1.5" is used to consider possible lithological variability and the Cbi parameter in the Igeo equation represents the geochemical background value (Bayraklı and Dengiz, 2020). As a result of the calculations, the classification process was carried out according to Teng et al. (2002) (Figure 2).

Enrichment factor	**Sediment quality**
EF < 2	Deficiency to minimal enrichment
2 < EF < 5	Moderate enrichment
5 < EF < 20	Significant enrichment
20 < EF < 40	Very high enrichment
EF > 40	Extremely high enrichment

Igeo value	**Pollution class**
Igeo < 0	Practically uncontaminated
0 < Igeo < 1	Uncontaminated to moderately uncontaminated
1 < Igeo < 2	Moderately contaminated
2 < Igeo < 3	Moderately to heavily contaminated
3 < Igeo < 4	Heavily contaminated
4 < Igeo < 5	Heavily to extremely contaminated
5 < Igeo	Extremely contaminated

Figure 2. Classification for EF and Igeo

According to the basic statistical evaluations of heavy metals in Table 2 and the geostatistical maps in Figure 3, the enrichment factor for Chromium (Cr) varies between 0.42 and 3.07 at 0-20 cm depth, between 0.71 and 2.52 at 20-40 cm depth, between 0.62 and 2.87 at 40-60 cm depth and between 0.62 and 1.97 at 60-90 cm depth. EF values for Nickel (Ni) were found between 1.20 and 3.41 at 0-20 cm depth, between 1.34 and 3.20 at 20-40 cm depth, between 1.41 and 3.66 at 40-60 cm depth and between 1.37 and 3.49 at 60-90 cm depth. Lead (Pb) has EF values ranging from 0.82 to 3.53 at 0-20 cm depth, from 1.13 to 3.33 at 20-40 cm depth, from 1.02 to 3.25 at 40-60 cm depth and from 0.98 to 2.84 at 60-90 cm depth. The geoaccumulation index for chromium (Cr) varies between -2.66 and 0.27 at 0-20 cm depth, between -2.43 and -0.27 at 20-40 cm depth, between -2.51 and -0.44 at 40-60 cm depth and between -2.89 and -0.64 at 60-90 cm depth. The Igeo values for nickel (Ni) are between -1.72 and 0.27 at 0-20 cm depth, -1.94 and 0.28 at 20-40 cm depth, -1.96 and 0.32 at 40-60 cm depth and -2.16 and 0.42 at 60-90 cm depth. Lead (Pb) has Igeo values ranging from -2.22 to -0.06 at 0-20 cm depth, -2.28 to 0.17 at 20-40 cm depth, -2.40 to -0.33 at 40-60 cm depth and -2.60 to -0.33 at 60-90 cm depth.

Table 2. Basic statistical evaluations of laboratory analysis results of heavy metals chromium, nickel and lead

	Depth	Minimum	Maximum	Mean	Std. Error	Std. Deviation	Skewness	Kurtosis
Total Cr (ppm)	0-20	23.78	219.3	59.19	2.03	23.83	3.28	18.35
	20-40	26.28	198	59.91	1.82	21.42	2.34	11.92
	40-60	26.36	110.8	57.89	1.66	19.56	0.6	-0.35
	60-90	20.23	96.45	52.69	1.48	17.4	0.42	-0.41
Total Ni (ppm)	0-20	34.1	135.6	76.44	2.01	23.58	0.56	-0.36
	20-40	29.22	136.6	78.83	2.06	24.15	0.34	-0.55
	40-60	28.88	140.6	79.71	2.38	27.97	0.35	-0.69
	60-90	25.19	150.1	74.44	2.21	25.92	0.5	0.33
Total Pb (ppm)	0-20	4.01	18.97	10.22	0.23	2.76	0.79	0.23
	20-40	3.85	21.11	9.92	0.21	2.51	0.7	1.85
	40-60	3.56	49.74	12.54	3.55	41.67	11.67	13.67
	60-90	3.1	14.91	8	0.22	2.54	0.46	-0.17

With the heavy metal analysis results, both the enrichment factor and geoaccumulation index calculations were made and the geostatistical maps given in Figure 3 were prepared. In this mapping process, it was decided which parameter should be used with which method by comparing the RMS values and selecting the method with the smallest value (Table 3).

Table 3. RMSE values of parameters used in method selection of geostatistical maps

			Ef (Cr)	**Igeo (Cr)**	**Ef (Ni)**	**Igeo (Ni)**	**Ef (Pb)**	**Igeo (Pb)**
IDW		1	0.34715	0.39695	0.33242	0.30960	0.36448	0.31130
		2	0.33645	0.37590	0.30633	0.29070	0.35129	0.29747
		3	0.33135	0.36685	0.29004	0.28226	0.34738	0.29236
RBF		CRS	0.32774	0.36150	0.26445	0.27763	0.35175	0.29004
		ST	0.32899	0.36174	0.27074	0.27751	0.34828	0.29005
		TPS	0.34770	0.37749	0.27759	0.30667	0.40660	0.31299
Kriging	**Ordinary**	Spherical	0.33618	0.36870	0.29513	0.28049	0.34470	0.29173
		Exponential	0.33196	0.36464	0.28290	0.28278	0.34633	0.29230
		Gaussian	0.33742	0.37211	0.30322	0.28249	0.34502	0.29508
	Simple	Spherical	0.32796	0.36327	0.29037	0.28085	0.34248	0.29330
		Exponential	0.32022	0.35841	0.27980	0.28311	0.34598	0.29206
		Gaussian	0.32704	0.36399	0.29545	0.28432	0.34290	0.29505
	Universal	Spherical	0.33618	0.36870	0.29513	0.28049	0.34470	0.29173
		Exponential	0.33196	0.36464	0.28290	0.28278	0.34633	0.29230
		Gaussian	0.33742	0.37211	0.30322	0.28249	0.34502	0.29508

As a result of all these processes, it was determined that there was a significant risk in chromium and lead and a moderate risk in nickel in terms of enrichment factor in the areas close to the surface (Table 4). While no significant change was observed in nickel with increasing depth, it was observed that it decreased in chromium and lead. In the geoaccumulation index at the same depth, although chromium and lead were determined to be at a "low level" in the upper layers, it was determined that there was "no pollution" as the depth increased. In nickel, while it was at a "low level" in the upper layers, there was an increase towards "moderate level" in the lower layers. The reasons for the risk status determined in lead can be associated with the intensive industrial activities carried out around the region (Alloway 2013) and intensive agricultural practices (McLaughlin et al., 1999).

It is thought that the slight increase in the geoaccumulation index from the upper layers to the lower layers, which was determined specifically for nickel, may pose a risk for the future. This situation may be caused by phosphate-based fertilizers and some pesticides used for many years (McLaughlin et al., 1999), but the fact that no decrease is observed as the depth increases and even increases reveals that this situation may be due to the parent material.

Table 4: Basic statistical analysis results of the analysis results of the enrichment factor and geoaccumulation index

	Depth	Mean	Min	Max	St. Error	St. Dev.	Skewness	Kurtosis
Cr (EF)	0-20	1.35	0.42	3.07	0.03	0.33	4.74	0.84
	20-40	1.36	0.71	2.52	0.03	0.32	1.35	0.64
	40-60	1.36	0.62	2.87	0.33	0.33	2.85	0.77
	60-90	1.32	0.62	1.97	0.02	0.28	0.05	0.04
Ni (EF)	0-20	2.38	1.20	3.41	0.04	0.45	-0.78	-0.09
	20-40	2.38	1.34	3.20	0.04	0.44	-0.91	-0.12
	40-60	2.44	1.41	3.66	0.04	0.46	-0.57	0.21
	60-90	2.45	1.37	3.49	0.04	0.42	-0.47	0.13
Pb (EF)	0-20	1.90	0.82	3.53	0.03	0.36	3.13	0.72
	20-40	1.83	1.13	3.33	0.03	0.36	3.19	1.24
	40-60	1.67	1.02	3.25	0.03	0.33	3.80	1.17
	60-90	1.59	0.98	2.84	0.02	0.28	4.42	1.34
Cr (Igeo)	0-20	-1.45	-2.66	0.27	0.04	0.45	1.02	0.14
	20-40	-1.41	-2.43	-0.27	0.04	0.43	-0.19	0.01
	40-60	-1.45	-2.51	-0.44	0.04	0.49	-0.83	0.00
	60-90	-1.59	-2.89	-0.64	0.04	0.50	-0.26	-0.35
Ni (Igeo)	0-20	-0.61	-1.72	0.27	0.04	0.44	-0.39	-0.06
	20-40	-0.57	-1.94	0.28	0.04	0.46	-0.02	-0.38
	40-60	-0.59	-1.96	0.32	0.05	0.54	-0.33	-0.40
	60-90	-0.69	-2.16	0.42	0.05	0.54	0.44	-0.61
Pb (Igeo)	0-20	-0.93	-2.22	-0.06	0.03	0.37	0.17	0.04
	20-40	-0.96	-2.28	0.17	0.03	0.37	0.87	-0.32
	40-60	-1.14	-2.40	-0.33	0.04	0.47	-0.74	-0.36
	60-90	-1.30	-2.60	-0.33	0.04	0.48	-0.14	-0.34

Conclusion

In this study, firstly Cr, Ni and Pb accumulations in the area were determined as a result of the analyses performed together with soil samples. In the next stage, these results were calculated with the enrichment factor and geoaccumulation index formulas, and the future risk potential of heavy metals in the area was evaluated. In addition, with soil samples taken from different depths, it was examined whether the source of heavy metals could be from the parent material or human-made. As a result of the risk assessments, no situation that was considered very risky for the future was determined. While the source of chromium and lead heavy metals was thought to be mostly human and environmental, it was concluded that nickel could be both environmental and parent material-based. With all these evaluations, the status of this type of heavy metals, which are extremely dangerous for living things and the environment, and the potential risks that may occur for the future have been revealed. It is essential to further examine this issue with more comprehensive heavy metal studies.

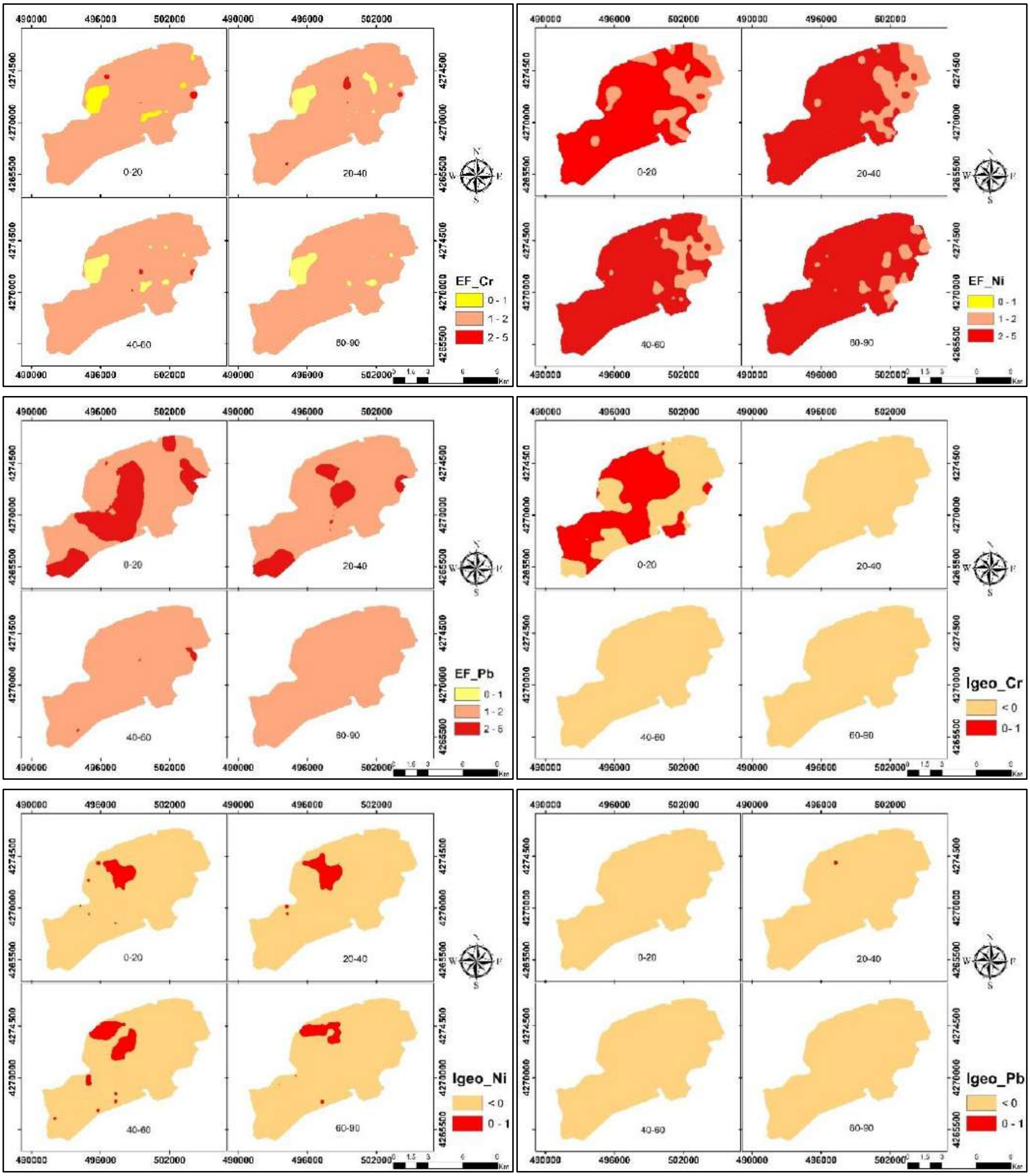


Figure 3. Geostatistical maps of the enrichment factor and geoaccumulation index results for chromium, nickel and lead

References

Cemek, B. and Kizilkaya, R. (2006). Spatial variability and monitoring of Pb contamination of farming soils affected by industry. Environmental monitoring and assessment, 117, 357-375.

Chen, Y., Wang, H., and Zhang, L. (2021). Chromium contamination and its ecological risks in industrial zones. Environmental Research, 192, 110291. Liu, X., Zhao, Y., Huang, Z. (2020). Bioremediation strategies for heavy metal-contaminated soils. Science of the Total Environment, 743, 140740.

Gupta, A., Singh, R., Kumar, P. (2021). Heavy metal contamination in agricultural soils: Risks and remediation. Journal of Environmental Science and Health, 56(8), 1234 -1245.

Kabata-Pendias, A., Pendias, H. (2001). Trace Elements in Soils and Plants. CRC Press McLaughlin, M. J., Parker, D. R., & Clarke, J. M. (1999). "Metals and micronutrients - food safety issues." Field Crops Research, 60(1-2), 143-163 Alloway, B. J. (2013). Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability. Springer.

Müller, G. (1969). "Index of geoaccumulation in sediments of the Rhine River." Geology Journal, 2, 109-118.

Özden N, Kayam Y, Beyazgül M, Korkmaz N, Atiş İ, Üner K, Gündüz M, Malli T, Eryiğit N. (2009). Use of updatable land information system in soil and water management at irrigation network level. Ministry of Agriculture and Forestry Tagem Research Final Report

Özden N., Uslu İ., Sen S., Sokmen O., Candan N., Aras S., Metinoglu F., Alkan U., Rahmanoglu N., Sen O. F., Gocmez S. (2019). Plant Nutrient Content of Agricultural Soils in Izmir, Manisa and Aydin Provinces and Determination of Potential Toxic Element Scopes, Creation of Database and Mapping. Ministry of Agriculture and Forestry Tagem Research Result Report

Bayraklı, B., Dengiz, O. (2020). An evaluation of heavy metal pollution risk in tea cultivation soils of micro-catchments using various pollution indexes under humid environmental conditions. Rendiconti Lincei. Scienze Fisiche e Naturali, 31(2), 393-409.

Smith, J., Jones, M. (2022). Nickel pollution in European farmlands: Implications for food security. Environmental Pollution, 276, 117286.

Sutherland, R. A. (2000). "Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii." Environmental Geology, 39(6), 611-627.

Teng, Y. G., Tuo, X. G., Ni, S. J., Zhang, C. J. (2002). Applying geoaccumulation index to assess heavy metal pollution in sediment: influence of different geochemical background. Environmental Science and Technology, 2, 7-9.

Tepecik, M., Özen, F., Bolca, M., Kayıkçıoğlu, H. H., İlbi, H., Bayram, S. E. (2022). Determination of fertility status and creation of maps of Menemen plain entisol soils. ANADOLU Journal of Aegean Agricultural Research Institute, 32 (2), 143-160.

UTAEM (2019). MGM Weather Station Records. Menemen-İzmir

Wuana, R. A., Okieimen, F. E. (2011). "Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation." ISRN Ecology.

The impact of soil conditioners on soil quality and conservation

Neysa Marelin MAMANI ZENTENO*, Coşkun GÜLSER
Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Neysa Marelin MAMANİ ZENTENO
mz.neysamarelin@gmail.com

Abstract

The worldwide demand for food production has increased due to population growth, technological developments, and the rapid expansion of agricultural territory, placing an enormous demand on soil resources. Soil erosion, declining fertility, and environmental degradation threaten the sustainability of agro-ecosystems. In order to overcome these challenges, soil conditioner, which are composed from both organic and inorganic materials have become essential tools for improving the biological, chemical, and physical characteristics of soil. Soil conditioners are promising tactic to improve soil productivity since their material contain essential nutrients that enhance soil properties. This review explores the classification, mechanisms, increased nutrient availability, and better microbial activity and influence of soil conditioners on soil quality parameters, the challenges and considerations associated with their application. The paper highlights the potential of soil conditioners in reducing erosion risks, improving soil fertility and promoting sustainable techniques based on researches which demonstrate the effective results of soil conditioners. However, challenges such as environmental impact, cost, and application constraints are critical considerations. Future directions in soil conditioning emphasize innovation, particularly through biodegradable and bio-recyclable polymers, to enhance agricultural productivity while reducing ecological footprints. By integrating soil conditioners into conservation practices, we can support resilient and sustainable agro ecosystems, thereby enhancing soil health and productivity.

Keywords: Soil conditioners, Soil quality, Soil conservation, Soil erosion

Introduction

The environment is under greater pressure due to the rapid rise in global production, which has a negative impact on soil, air and water resources (FAO, 2017). Therefore, innovative and efficient methods must be implemented to address critical soil challenges, including soil erosion, declining of soil fertility, environmental degradation. Soil has a critical role for the humanity since it influences to human health directly through the ingestion, inhalation and absorption of soil, it also has an indirect impact through the quantity and quality of food produced by soil-based agriculture. (Oliver M., Gregory P., 2015). Soil erosion is an environmental concern that constitutes a major negatively effect on soils, in fact, soils perform a range of key functions, including the production of food, the storage of organic matter, water and nutrients, the provision of a habitat for a huge variety of organisms and preserving the past human activity. Any degradation in the quality of the soil resource trough erosion can have an impact on the ability of soils to perform this range of functions (Morgan, 2009). A promising tactic to improve productivity and restore agricultural land is the incorporation of both organic and inorganic soil conditioners and soil additives. Soil conditioners involve techniques that support thriving crops and enhance the soil's ability to perform various functions. Their main benefit lies in their positive impact on the soil's biological, physical, or chemical properties, since the materials of soil conditioners contain important nutrients. These materials can be natural things like plants and microbes, or man-made substances like polymers and industrial waste products (Thakur P. et al., 2023). Soil conditioners can be applied to the upper layers of soil, where the root systems normally develop. It has been demonstrated that using soil conditioners can effectively give plants access to a reservoir of soil water (Babla, M. et al., 2022).

Soil conditioners can be classified on the basis of two criteria: origin of the materials, and composition of the materials (Shinde et al., 2019).

Organic Soil Conditioners: Material derived from living organisms, such as plants and animals. To enhance soil qualities and plant growth, organic materials have been used extensively as soil amendments (Chaudhari et al., 2021). Crop residues, manures, peat, biochar, bone meal, blood meal, coffee grounds, compost tea, coir, sewage sludges, farmyard manure, and sawdust (Shinde et al., 2019).

Inorganic Soil Conditioner: Manufactured by products, occurring naturally or synthetically to improve the soil physical properties, thereby enabling the successful utilization of soil and water resources (Shinde et al., 2019). Also contain mineral conditioners such as fly ash, sulfur, zeolites, phosphogypsum, pyrites, broken rocks, lime, and gypsum. Since the majority of them are alkaline materials rich in Si, Ca, K, and Mg, they are used to balance soil acidity (Yang et al., 2020).

Synthetic Soil conditioners: Polymers that may be applied at lower rates are the most common type of synthetic soil conditioner. These are long-chain, polymeric, organic molecules with a very high molecular weight that bind particles together to create stable aggregates. Organic polymers, primarily polysaccharides (PSD) and polyacrylamides (PAM), are commonly used to improve aggregate stability, preserve fertility, and reduce seal formation (Shinde et al., 2019).

This paper aims to provide a comprehensive overview of the impact of soil conditioners on soil conservation and soil quality, based on demonstrating evidences how soil conditioners contribute to mitigating erosion risks and enhancing soil conservation practices. By exploring their roles in improving soil structure, fertility and microbial activity among others.

Mechanisms of Soil Conditioners

Superabsorbent Hydrogels (SH) based on polysaccharides have been suggested for use in agricultural applications, due to their exceptional hydrophilic properties (high swelling capacity and high swelling rate), as well as their excellent biocompatibility and biodegradability (Guilherme M. et al, 2015). Besides superabsorbent polymer (SAP), referred as hydrogels is considered the most successful component of soil conditioners since can absorb up to 400 times their weight in water (Coello J. et al, 2018). In accordance with Wang Y., et al. (2013), the high-water absorption of these materials is attributed to the interconnected super pore structures with diameters of several hundred microns, creating open channels that allow for capillary action. In basic media, the concentration of anionic groups increases relatively, and electrostatic repulsion causes chain expansion as well as macroscopic expansion of SH as observed in Fig. 1 (Guilherme M. et al, 2015). In order to load the hydrogels with nutrients two strategies are used post loading and in situ loading is related to physical–chemical affinity of the fertilizer for polymer chains forming hydrogel. Due to its higher loading efficiency, the in-situ method is recommended over the post-loading one (Zheng Y. et al., 2007). First the loaded material is dried before adding to the crop, then the release is activated by swelling during the soil irrigations or during the rains. The water contained in the hydrogel dissolves nutrients, which can then be diffused through the polymer network (Martinez-Ruvalcaba A. et al., 2009). Therefore, when the hydrogel dries between irrigations or rains, some of the loaded solute remains within it thus the release is activated during watering processes, which contributes a prolonged release process that can stop the leaching. (Guilherme M., et al, 2015). Furthermore, PAMs applied to the soil surface reduce water erosion by stabilizing exposed soil aggregates, maintaining the integrity of soil macropores, reducing surface sealing and crusting, and promoting flocculation of suspended sediment. These mechanisms increase water infiltration, reduce runoff and soil loss, and reduce turbidity in runoff water resulting from rain or irrigation (Baumhardt R.L., 2014), however, the performance of PAM depends on soil properties and companion management practices (Flanagan et al., 2002).

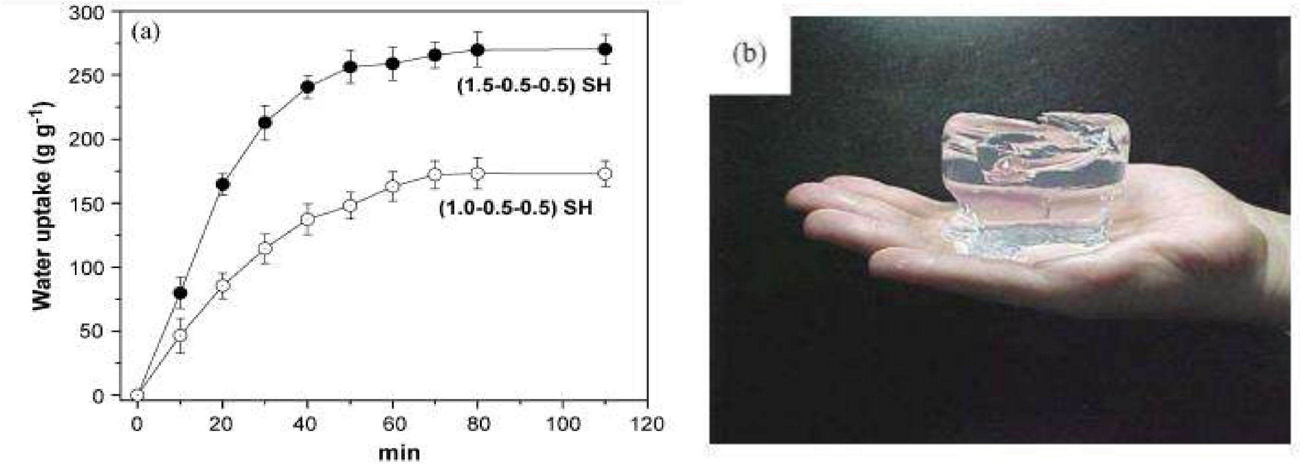


Fig. 1. (a) Water uptake capacity for (1.5–0.5–0.5) and (1.0–0.5–0.5) SH as a function of immersion time in water. (b) Picture of (1.5–0.5–0.5) SH swollen 275-fold from its own dry weight. (Paulino, A. T et al. 2006)

Influence on Soil Quality Parameters

Natural and synthetic soil conditioners can have a tremendous influence on the soil's physical, chemical, and biological properties. Plant-based by-products play a central role in recycling essential plant nutrients, sustaining soil fertility and reducing the toxicity of some heavy metals, which lead to increased yield with the proper dosages of the by-products (Hossain et al., 2016). For example, organic soil conditioner, biochar potentially enhances soil properties, soil health with microbial abundance, and biological nitrogen fixation thus improves agro-ecosystem sustainability in plant production (Das et al., 2021).

According with a research conducted by Zonayet et al. (2023), Biochar was applied on saline soil to prove the improvement on soil properties and tomato productivity. The biochar used was charcoal and agricultural byproducts pyrolyzed at 450°C and eight treatments were performed were the fifth treatment (T5=Recommended Fertilizer Dose plus 2 tons of biochar per hectare). Based on the results showed a potential improvement on the tomato height, number of fruits produced, and yield. According with the physical and chemical parameters applying biochar derived from wood charcoal improved soil quality by acting as a buffer (Table 1).

Table 1. Effect of biochar with RFD on bulk density, particle density, soil porosity, soil pH, EC, and salinity in post-harvest soil of tomato cultivation over control (Zonayet et al.., 2023)

Treatments	Bulk Density (g/cc)	Particle Density (g/cc)	Soil Porosity %	Soil pH	EC (µS/cm)	Salinity (ppt)
T_1	1.63 f	2.65 e	30.33 g	7.84 f	2800	0.6 c
T_2	1.29 c	1.98 d	39.75 bc	7.13 e	2400	0.6 c
T_3	1.19 d	1.34 bc	41.65 c	6.39 bc	600	0.4 b
T_4	0.9 b	1.21 b	46.54 b	6.19 cd	500	0.4 b
T_5	1.037 a	1.08 a	48.65 a	6.51 a	100	0.1 a
T_6	1.08 cd	1.31 bc	38.47 d	6.10 d	200	0.2 b
T_7	1.04 e	1.29 c	32.21 f	6.62 b	600	0.4 a
T_8	1.12 e	1.27 c	33.56 e	6.23 c	200	0.2 a
$LSD_{(0.05)}$	0.098	0.096	1.89	0.085	0.067	0.043
CV (%)	1.007	1.64	1.57	0.081	4.78	1.037

A research study regarding the impact of soil conditioners on the properties, soil microbial diversity and community structure, and soil enzyme activities of Uncaria rhynchophylla was conducted by Liu Q. et al. (2024). Five different soil conditioners (biomass ash, water retention agent, biochar, lime powder, malic acid) were selected in order to evaluate the efficacy on improving the yield and quality of Uncaria rhynchophylla. The results were the following, the increased application of soil conditioner alleviated soil acidification compared to the application of green manure and chemical fertilizer alone. Specifically, the biomass was determined as an ideal soil conditioner for agricultural activities which can improve the soil environment and increase the nutrient content. Biomass showed results at improving soil properties, enzyme activities and soil microbial community structure, increasing the abundance of the Acidobacteria and decreasing Chloroflexi (Fig. 2).

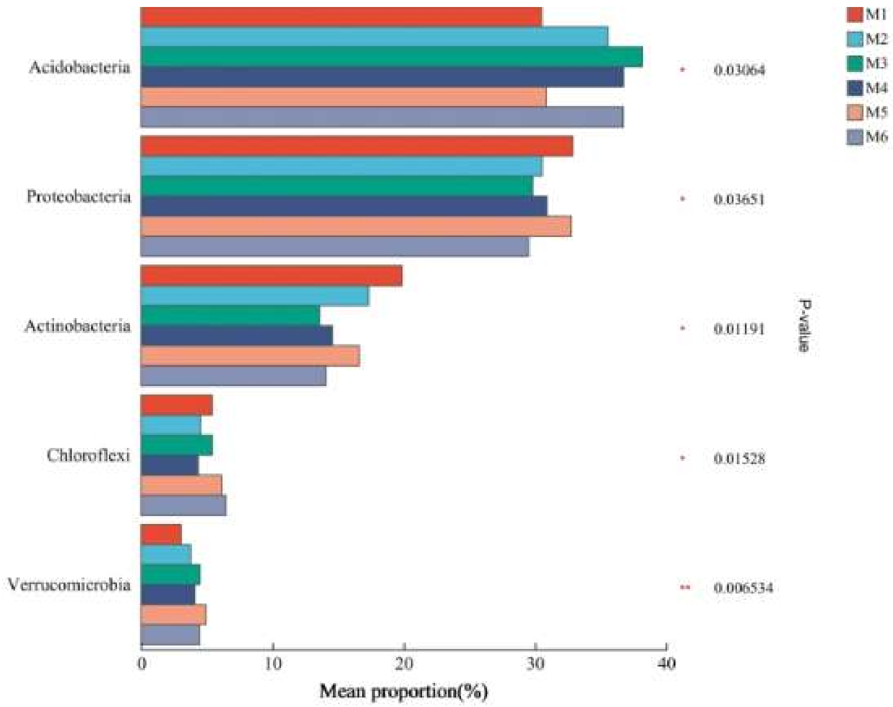


Fig. 2. (a) Relative abundances of bacterial phyla in the Uncaria rhynchophylla; M1 (no soil conditioner), M2 (biomass ash), M3 (water retention agent), M4 (biochar), M5 (lime powder), M6 (malic acid). (Liu Q. et al., 2024)

Role of Soil Conditioners in Soil Conservation

Practices for soil conservation are implemented in order to control erosion. For instance, wind erosion practices increase the size of exposed soil aggregates beyond their capacity to entrain wind thus reduces the wind speed to avoid entrainment of sediments and providing a barrier between the soil and wind. Conservation practices combat water erosion and involve a range of approaches like enhancing mechanical structures, agronomic or biological methods, conservation buffers, cover crops, and the application of soil conditioners. Soil conditioners are used to enhance the qualities of soil and reduce water erosion, for example: PAMs, flue gas desulfurization (FGD) gypsum, and phosphogypsum (PG) are some conditioners used to decrease water erosion (Baumhardt R.L., Blanco-Canqui H., 2014). In the case of Polyacrylamide (PAM), even at small amounts can significantly reduce soil erosion, it is effective at stabilizing surface structure, used for erosion control, and for infiltration improvement. PAM used with irrigation for erosion control benefits water quality in various ways (Sojka et al., 2004). In accordance with Karaoglu (2018), soil conditioners have an effect on water erosion by applying phosphogypsum (PG) and polyacrylamide (PAM). The application of both soil conditioners was on three different soil textures such as clay loam, sandy loam and loam. PAM application increased the infiltration values, comparing with PG values (Table 2). Once the soil samples reached saturation, the infiltrattion was measured 6 times with 10 minutes interval. PAM was 10% more effective and PG decreased the sediment concentration in runoff volume.

Table 2. Infiltration values (mm.m-2.h-1) (Karaoglu, 2018).

Clay Loam	**1**	**2**	**3**	**4**	**5**	**6**	**Total**
C	10.0	8.6	8.0	6.0	4.7	4.5	41.8
PAM	14.0	12.6	10.1	9.3	7.8	7.8	61.6
PG	13.4	11.9	9.9	8.6	7.0	7.0	57.8
Sandy Loam	**1**	**2**	**3**	**4**	**5**	**6**	**Total**
C	11.2	9.6	8.5	6.8	5.2	4.8	46.1
PAM	14.7	13.1	10.8	9.1	8.1	8.1	63.9
PG	13.7	12.4	9.9	8.8	7.4	7.4	59.6
Loam	**1**	**2**	**3**	**4**	**5**	**6**	**Total**
C	10.5	9.0	8.2	7.3	5.1	4.4	44.5
PAM	14.0	12.6	11.2	9.6	7.5	7.5	62.4
PG	13.7	11.9	10.2	8.0	6.9	6.9	57.6

C: Control, PAM: Polyacrylamide, PG: Phosphogypsum.

Another highly effective combination for reducing soil erosion and enhancing land productivity, particularly in acidic soils such as Oxisols, is the application of PAM with lime (Kebede B., et al., 2020). Additionally, better outcomes in mitigating water erosion may be achieved when PAM is applied in combination with phosphogypsum, FGD, and other soil conditioners, rather than using each product individually, for instance, PAM can be used as temporary stabilization practices in disturbed soils until a permanent surface cover is established. Nonetheless, soil conditioners are not a substitute to soil conservation practices but should be used as companions to other practices. To achieve successful conservation practices such as modifying field features, employing tillage methods, and managing crop rotations to enhance cover and retain residue can be effectively combined with the use of soil conditioners (Baumhardt R.L., Blanco-Canqui H., 2014).

Challenges and Considerations

The accumulation of microplastics represent a challenge that requires attention and with sustainable solutions. Plastics contaminate the environment and become a problem, thus, utilizing biodegradable and biorecyclable polymers could be a potential way to address this issue since they could reduce the amount of harmful pollutants released into the environment (Lewicka, K. et al., 2024). Nonetheless, the biodegradable polymers in agriculture became an alternative to traditional plastic materials such as poly (vinyl alcohol) (PVA), poly(adipate-co-terephthalate) (PBAT), poly (butylene succinate-co-adipate) (PBSA), and poly lactic acid (PLA). These polymers are designed to break down quickly and safely in the environment, reducing the negative effects of plastic waste on rivers and land. Using biodegradable polymers in agriculture has several advantages beyond waste reduction, such as improved soil health and higher crop yields (Verma K. et al., 2023). Therefore, the challenge comes with the application of polymers and the use of biodegradable polymers in seed coating since it is an important step toward environmentally friendly and sustainable agriculture. Coatings that are biodegradable reduce the possibility of plastic building up in soil and water, promoting thriving ecosystems and reducing the harmful consequences of plastic pollution. Overcoming these obstacles and enhancing the effectiveness and accessibility of biodegradable coatings are the main goals of research and development (Afzal, I., et al, 2020). Another significant challenge is the cost and economic viability, as high expenses have often limited the widespread use of soil conditioners, transportation costs are frequently more substantial than the cost of the materials themselves. Factors such as bulkiness, transportation logistics, application processes, and associated costs make it challenging to integrate soil conditioners into traditional production agriculture on a large scale. As a result, the use of conventional soil conditioners in large-scale operations has primarily been limited to cost-effective options such as lime, gypsum, and manure (Sojka, R.E., 2004).

Future Directions of Soil Conditioners

The future of soil conditioners might be anchored to the innovative technology developed and based on Polymers, synthetic soil conditioners. According to Lewicka K. (2024), due to the structure of the chain of these macromolecules can be changed based on the final use of polymers to create materials with a variety of qualities, including stiffness, flexibility, elasticity, and degradability. Because of their versatility, polymers can be developed for application in a wide range of industrial sectors, including as agricultural, electronics, automotive, construction, and packaging. The future of soil conditioners is also likely to depend on innovative researches from scholars who seek to investigate and develop sustainable solutions for soil challenges. For example, Liu S., et al. (2017) simulated a soil formation and prepared a novel nano-submicron mineral based soil conditioner by using an environmentally friendly hydrothermal method to buffer acidification and inhibit hazardous elements in soil, this approach can be used as a basis for new agricultural revolution. Also, a study conducted by Liu Y. et al. (2022) on DewEco, a new soil conditioner composed of fermenter organic material containing of L-lysine salt and citric acid and based on the results DewEco significantly improved soil water-holding capacity and moisture content in sandy soils used for maize cultivation (Fig. 3). The research demonstrated that this conditioner impacted in a positive way the physical and chemical properties of sandy soils in arid and semi-arid regions, highlighting its effectiveness as an eco-friendly tool for enhancing soil quality. Furthermore, DewEco requires considerably less dosages and has positive impacts on plant growth far faster than other popular organic conditioners such as manure, peat, crop residues, and biochar. Compared with existing synthetic soil conditioners such as polyacrylamide (PAM), showed to be superior in terms of enhancing soil texture and nutrient levels.

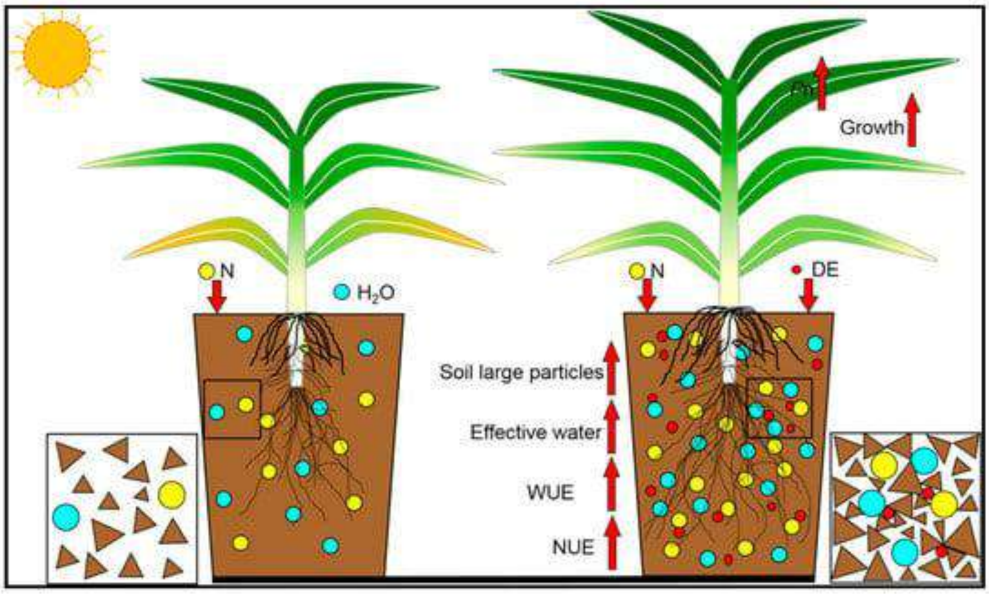


Fig.3. A schematic model of DewEco application on sandy soil quality. DewEco application could improve soil texture, decrease particle pore size, increase content of large particles, increase capacity for water retention and improve fertility, decrease soil pH and increase soil EC and nutrient contents, which together contribute to enhancing plant growth. (Liu, Y., et al, 2022)

Conclusion

Soil conditioners play a crucial role in enhancing soil properties, promoting plant growth, and contributing to sustainable agricultural practices. By improving soil structure, nutrient availability, water retention, and microbial activity, they provide means to combat soil erosion and degradation while boosting productivity. Despite challenges such as high costs, environmental impacts, and application logistics, the continued development of innovative, biodegradable, and cost-effective solutions can significantly enhance their efficacy and adoption. Advancing research and sustainable practices will be key to unlocking the full potential of soil conditioners, supporting resilient and productive agro-ecosystems for future generations.

References

Afzal, I.; Javed, T.; Amirkhani, M.; Taylor, A.G. Modern Seed Technology: Seed Coating Delivery Systems for Enhancing Seed and Crop Performance. Agriculture 2020, 10, 526.

Babla, M., Katwal, U., Yong, M. T., Jahandari, S., Rahme, M., Chen, Z. H., & Tao, Z. (2022). Value-added products as soil conditioners for sustainable agriculture. Resources, conservation and recycling, 178, 106079.

Baumhardt R.L., Blanco-Canqui H. Soil: Conservation Practices. In: Neal Van Alfen, editor-in-chief. Encyclopedia of Agriculture and Food Systems, Vol. 5, San Diego: Elsevier; 2014. pp. 153-165.

Chaudhari, S., Upadhyay, A., Kulshreshtha, S., 2021. Influence of organic amendments on soil properties, microflora and plant growth. Sustainable Agriculture Rev. 52, 147–191. Springer.

Coello, J., Ameztegui, A., Rovira, P., Fuentes, C., & Piqué, M. (2018). Innovative soil conditioners and mulches for forest restoration in semiarid conditions in northeast Spain. Ecological Engineering, 118, 52-65.

Das, S., Mohanty, S., Sahu, G., Rana, M., Pilli, K., 2021. Biochar: a sustainable approach for improving soil health and environment. Soil Erosion-Current Challenges and Future Perspectives in a Changing World, 121–138.

FAO (Food and Agriculture Organization), 2017. The State of Food and Agriculture: Leveraging Food Systems for Inclusive Rural Transformation. United Nations Food and Agriculture Organization, Rome, Italy

Flanagan, D.C., Chaudhari, K., Norton, L.D., 2002. Polyacrylamide soil amendment effects on runoff and sediment yield on steep slopes: Part II. Natural rainfall conditions. Transactions of the American Society of Agricultural Engineers 45, 1339–1351

Guilherme M. R., Aouada, F. A., Fajardo, A. R., Martins, A. F., Paulino, A. T., Davi, M. F., & Muniz, E. C. (2015). Superabsorbent hydrogels based on polysaccharides for application in agriculture as soil conditioner and nutrient carrier: A review. European Polymer Journal, 72, 365-385.

Hossain, M.Z., von Fragstein, P., Heß, J., Heß, J., 2016. Plant origin wastes as soil conditioner and organic fertilizer: a review. J. Agric. Environ. Sci. 16, 1362–1371.

Karaoglu, M., & Acar, F. (2018). Determining the effects of soil conditioners on water erosion in soils with different textures by using rainfall simulator. Fresenius Environmental Bulletin, 27, 5244-5251.

Kebede, B., Tsunekawa, A., Haregeweyn, N., Mamedov, A. I., Tsubo, M., Fenta, A. A., & Berihun, M. L. (2020). Effectiveness of polyacrylamide in reducing runoff and soil loss under consecutive rainfall storms. Sustainability, 12(4), 1597.

Lewicka, K., Szymanek, I., Rogacz, D., Wrzalik, M., Łagiewka, J., Nowik-Zając, A., & Rychter, P. (2024). Current Trends of Polymer Materials' Application in Agriculture. Sustainability (2071-1050), 16(19).

Liu, Q., Cui, H., Yang, W., Wang, F., Liao, H., Zhu, Q.,& Lu, P. (2024). Soil conditioner improves soil properties, regulates microbial communities, and increases yield and quality of Uncaria rhynchophylla. Scientific Reports, 14(1), 13398.

Liu, S., Qi, X., Han, C., Liu, J., Sheng, X., Li, H., ... & Li, J. (2017). Novel nano-submicron mineral-based soil conditioner for sustainable agricultural development. Journal of Cleaner Production, 149, 896-903.

Liu, Y., Yan, M., Na, K., Hwang, J., Shin, S., Yin, L., ... & Wang, S. (2022). The new soil conditioner DewEco could improve sandy soil's properties for efficient maize growth. Agronomy, 12(5), 1124.

Martinez-Ruvalcaba, J.C. Sanchez-Diaz, F. Becerra, L.E. Cruz-Barba, A. Gonzalez-Alvarez, Swelling characterization and drug delivery kinetics of polyacrylamide-co-itaconic acid/chitosan hydrogels, Express Polym. Lett. 3 (1) (2009) 25–32.

Morgan, R. P. C. (2009). Soil erosion and conservation. John Wiley & Sons.

Oliver, M. A., & Gregory, P. J. (2015). Soil, food security and human health: a review. European Journal of Soil Science, 66(2), 257-276.

Paulino, A. T., Guilherme, M. R., Reis, A. V., Campese, G. M., Muniz, E. C., & Nozaki, J. (2006). Removal of methylene blue dye from an aqueous media using superabsorbent hydrogel supported on modified polysaccharide. Journal of colloid and interface science, 301(1), 55-62.

Shinde, R., Sarkar, P.K., Thombare, N., 2019. Soil conditioners. Agric. Food: e-Newsl. 1, 1–5.

Sojka, R.E., Orts, W.J., Entry, J.A., 2004. Soil physics and hydrology: Conditioners. In: Hillel, D. (Ed.), Encyclopedia of Soil Science. Oxford, UK: Elsevier, pp. 301–306.

Thakur, P., Shubham, H. W., & Kaushal, S. (2023). Soil Conditioners: Refinement of Soil Health for Better Tomorrow. Current Journal of Applied Science and Technology, 42(42), 1-9.

Verma, K.; Sarkar, C.; Adam, S. Biodegradable Polymers for Agriculture. In Biodegradable Polymers and Their Emerging Applications; Saha, S., Sarkar, C., Eds.; Materials Horizons: From Nature to Nanomaterials; Springer: Berlin/Heidelberg, Germany, 2023; pp. 191–212.

Wang, Y., Shi, X., Wang, W., & Wang, A. (2013). Synthesis, characterization, and swelling behaviors of a pH-responsive CMC-g-poly (AA-co-AMPS) superabsorbent hydrogel. Turkish Journal of Chemistry, 37(1), 149-159.

Y. Zheng, P. Li, J. Zhang, A. Wang, Study on superabsorbent composite XVI. Synthesis, characterization and swelling behaviors of poly(sodium acrylate)/vermiculite superabsorbent composites, Eur. Polym. J. 43 (5) (2007) 1691–1698

Yang, X., Feng, Y., Zhang, X., Sun, M., Qiao, D., Li, J., Li, X., 2020. Mineral soil conditioner requirement and ability to adjust soil acidity. Sci. Rep. 10, 1–12.

Zonayet, M., Paul, A. K., Faisal-E-Alam, M., Syfullah, K., Castanho, R. A., & Meyer, D. (2023). Impact of biochar as a soil conditioner to improve the soil properties of saline soil and productivity of tomato. Sustainability, 15(6), 4832.

Soil quality assessment in Aksu village, Samsun: A SMAF model approach across different land use types

Nimeshi WIJEKOON [1,2] *, Orhan DENGIZ [1], Sena PACCI[1]

[1] Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye
[2] University of Agriculture in Krakow. Department of Soil Science and Soil Protection; Kraków, Poland

***Corresponding Author**

Nimeshi WİJEKOON
nswnimeshi@gmail.com

Abstract

The quality of soil plays a crucial role in environmental health and agricultural productivity, demonstrating the soil's capacity to support plant growth, preserve water quality, and sustain microbial populations. Land use patterns have a profound impact on soil quality, primarily through their effects on soil structure, nutrient accessibility, and biological processes. In contrast to traditional soil testing methods that often provide isolated measurements of specific soil characteristics, the Soil Management Assessment Framework (SMAF) offers a holistic and methodical approach to soil quality evaluation. This framework incorporates a wide range of chemical, physical, and biological indicators to provide a comprehensive assessment. The primary aim of this study is to assess soil quality across various land use types, including pasture, forest, and cultivated areas, in Aksu Village, located on the southern coast of the Black Sea region. To achieve this, a total of 54 soil sampling points were designated through land use areas, covering approximately 486 ha. The SMAF model was employed for the evaluation, utilizing 12 different indicators that represent the physical, chemical, and biological properties of the soil. The results indicate that the overall physical soil quality falls within the medium range, while the chemical quality is classified as high across all land use types. Additionally, the overall biological soil quality is evaluated as very high. Specifically, the physical quality of soil in pasture lands is categorized as low, whereas in cultivated and forest lands, it is classified as medium. Conversely, the chemical quality across all land use types is classified as high, while the biological quality is categorized as very high. In conclusion, the general soil quality of the study area is assessed as high, highlighting the critical role of soil quality and land use in effective land management and sustainable agricultural practices.

Keywords: Indicators, Land use types, Soil Management Assessment Framework, Soil quality

Introduction

Agricultural sustainability and environmental well-being heavily depend on soil quality, which encompasses the chemical, physical, and biological attributes of soil (Palojärvi and Nuutinen, 2002) This concept is fundamental to crop yields, worldwide nutrient cycles, and ecosystem operations (Palojärvi and Nuutinen, 2002). Although the chemical aspects of soil quality have been extensively researched, further investigation into its physical and biological elements is necessary (Palojärvi and Nuutinen, 2002). A primary indicator of soil quality is organic matter content, and understanding soil quality requires examining the interactions within the soil-plant-biota system (Vezzani and Mielniczuk, 2009). The term soil health, often interchangeable with soil quality, highlights the dynamic, living nature of soil (Pachani and Kashyap, 2020). Evaluating soil quality and ensuring robust crop production involves assessing various physico-chemical characteristics, including pH levels, electrical conductivity, moisture content, texture, and nutrient composition (Patel, Rathwa et al., 2022). To maintain long-term agricultural productivity and sustainability, it is essential to continuously monitor these soil properties (Pachani and Kashyap, 2020) ;(Patel et al., 2022).

Currently, soil degradation has emerged as a critical global issue, primarily driven by various human-induced activities such as intensive agriculture, deforestation, urbanization, overgrazing, industrial pollution, and unsustainable land-use practices, therefore soil quality assessment in various land use types are essential for sustainable land management and human health (Zornoza et al., 2014). Multiple indicators, encompassing physical, chemical, and biological properties, are requisite for a comprehensive evaluation (Zornoza et al., 2014; Bone et al., 2010). Soil organic carbon and pH are frequently utilized indicators, whereas microbial biomass and enzyme activities are less commonly employed (Zornoza et al., 2014). The integration of indicators into a soil quality index (SQI) provides consolidated information regarding soil processes and functioning (Kalu et al., 2015; Mulat et al., 2021). Land use significantly influences soil quality, with forests generally demonstrating higher SQI compared to cultivated lands (Kalu et al., 2015; Mulat et al., 2021). Appropriate fertilizer application and organic farming practices are recommended to enhance soil quality in agricultural areas (Kalu et al., 2015). The development of a systematic method utilizing cross-functional indicators could efficiently prioritize areas for detailed investigation and support soil protection legislation (Bone et al., 2010).

The Soil Management Assessment Framework (SMAF) is a methodical approach for evaluating soil quality by incorporating diverse indicators that represent the chemical, physical, and biological attributes of soil. This framework offers location-specific interpretations of soil quality indicators, enabling customized assessments based on management objectives, climate conditions, crop types, and soil characteristics. The fundamental steps of SMAF involve selecting pertinent indicators that reflect soil quality across chemical, physical, and biological dimensions, and utilizing non-linear scoring curves to convert raw data into standardized scores ranging from 0 to 1 (Andrews et al., 2004).

SMAF has been employed in various scenarios to evaluate soil quality changes resulting from different land uses and agricultural methods. It aids in identifying primary soil constraints and prioritizing management strategies. The framework's application has extended to diverse environments, including research in Brazil that showcased its efficacy in detecting soil quality variations across different management practices (Cherubin et al., 2016). The adaptability of SMAF to various soil types and management systems makes it a crucial tool for farmers, land managers, and policymakers striving for sustainable land utilization. Individual indicator scores are combined to create an overall Soil Quality Index (SQI) that represents the performance of soil functions such as crop productivity and nutrient cycling. Developed by (Andrews and Carroll, 2001), SMAF is supported by empirical research validating its effectiveness in assessing soil quality. The primary objective of this study is to assess soil quality across various land use types, including pasture, forest, and cultivated lands, within Aksu Village, located in Samsun base on Soil Management Assessment Frame work (SMAF) model.

Material and Methods

Study Area

The study area for this research is the southern coast of the Black Sea, covering 486 ha. Geographically, it is located between 41°20'15'' and 41°21'31''N latitude, and 36°08'40'' and 36°11'00''E longitude. According to the International Soil Reference and Information Centre (ISRIC) WRB soil classification system, the region is predominantly covered by Haplic Cambisols, followed by Haplic Luvisols and Rendzic Leptosols. The elevation of the area ranges between 127.6 and 565.2 meters above sea level (m.a.s.l.) (Figure 1).

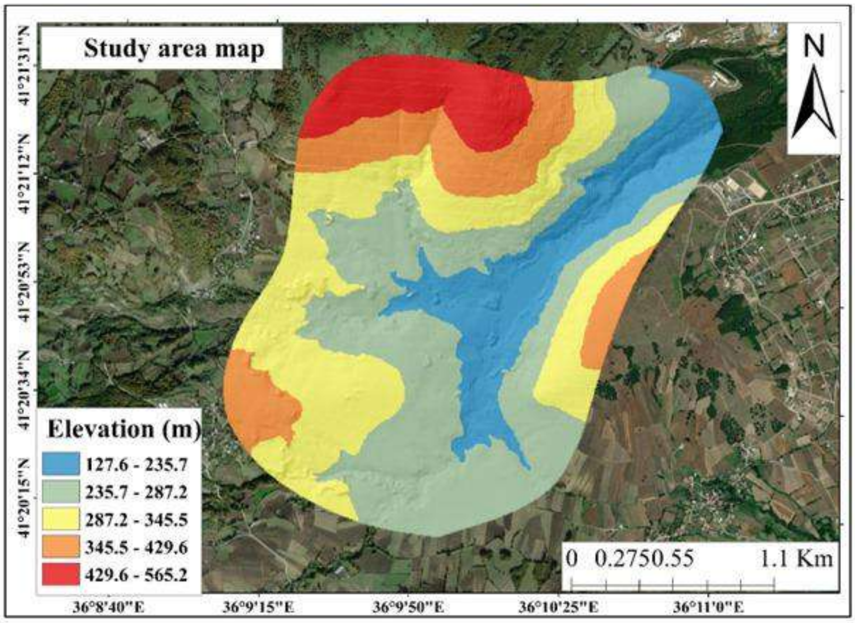


Figure 1. Study area map

Soil Sampling and analysis

Using ArcGIS software, 54 sampling points were spread randomly throughout the study region.25 sampling stations were on forest land, 16 were on cultivated land, and the remaining 13 were on pasture. A soil sample was collected from the top layer of these samples.

The soil quality parameters investigated in this study, depending on the type of land use, included soil textural classes (clay, silt, and sand), organic matter content, bulk density, available water content, electrical conductivity, pH, aggregate stability, organic matter classification, climate, mineral content, slope and weathering, season, magnesium, phosphorus, Calcium, Sodium and microbial biomass. These parameters were selected and analyzed for each land use type based on the principles outlined in Table 1.

Table 1. Soil quality parameters

Parameter	Principle/Method	Reference
Texture	Hydrometer method	Bouyoucos, 1951
Bulk Density	SPAW Model, Soil water characteristics	Soil water characteristics
Available Water Content	SPAW Model, Soil water characteristics	Soil water characteristics
Aggregate Stability	Wet Sieving	Kemper & Rosenau, 1986
pH	Soil water suspension	Burt, 1992
Electrical Conductivity	Soil water suspension	Burt, 1992
Total Carbon	Walkley-Black wet digestion	Nelson & Sommers, 1982
Available Water Content	Difference of FC and PWP	Klute, 1986
Microbial Biomass Carbon	Microbial induced respiration method	Anderson & Domsch, 1978
Phosphorus	Bray and Kurtz (pH < 7), Olsen (pH > 7)	Kacar, 1994
K, Ca, Mg, Na	Ammonium acetate extraction, flame spectrometry detection	Burt, 1992; Loch & Rosewell, 1992

SMAF Model Analaysis

The Soil Management Assessment Framework (SMAF) offers location-specific interpretations of soil quality indicator outcomes. A site's soil quality is influenced by factors such as land type, management practices, climate, soil varieties, and crop types (Andrews et al., 2004). This framework's model approach adapts to the necessary variations in site- and objective-specific interpretations of indicator results. The framework is composed of three primary phases: Indicator Selection, Indicator Interpretation, and Indicator Score Combination in this research, we implemented the SMAF model by following these three stages, utilizing 12 indicators grouped into physical, chemical, and biological categories. These indicators include available water content, water-filled pore volume, bulk density, aggregate stability, soil organic carbon content, soil pH, electrical conductivity, sodium adsorption rate, plant-available phosphorus and potassium, potential mineralizable nitrogen, and microbial biomass carbon. This methodology aided in monitoring crucial soil functions within our chosen study area. The study's findings evaluated the soil's capacity to perform the functions necessary for its intended purpose (Figure 2).

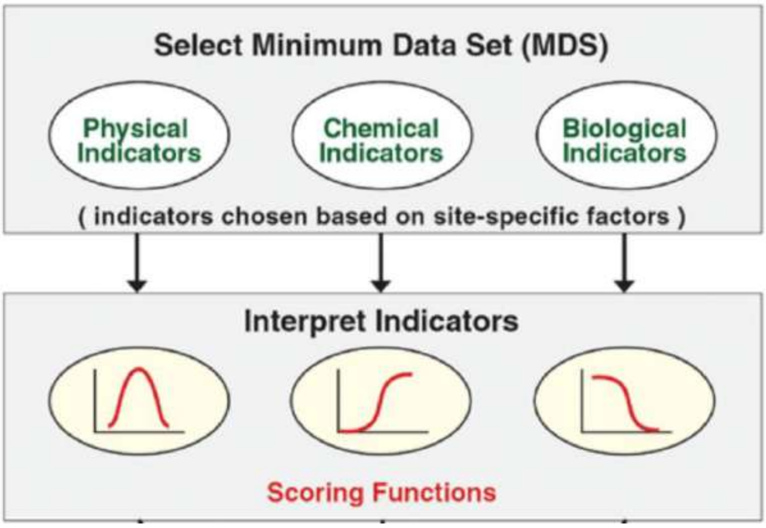


Figure 2. Indicator interpretation (Andrews & Carroll, 2001)

The model employs nonlinear scoring functions for evaluation. This widely utilized concept was initially implemented by Karlen and Stott (1994) in both the interpretation and scoring of soil indicators. For this purpose, researchers utilized three primary scoring curves. These scoring curves (Figure 2) are categorized as "more is better," "less is better," and "the middle point is optimum (Pacci et al., 2021). Each SMAF scoring curve incorporates an algorithm or a logical expression with an alternative algorithm. The algorithms in the model represent quantitative relationships between the empirical values of the measured indicators and the normalized scores (Pacci et al., 2021).

The process of incorporating the values obtained from the indicators into a single index facilitates the comprehensive evaluation of soil quality and enables the understanding of the effects of applied management practices on soil functions. To achieve this, the SMAF model utilizes the additive index method (Pacci et al., 2021) In the additive index calculation, the value from each indicator is summed and divided by the number of indicators. When the result is multiplied by 100, the soil quality, which is expressed as the capacity of the soil to demonstrate the determined function, is quantified as a percentage.

Soil quality index is calculated with the formula below,

$$SQI = (\frac{\sum_i^n Xi}{n}) \times 100$$

Soil quality index, Xi: scoring indicator value, n: indicator number.

In the classes for soil quality scoring, if the results are below 40, it is evaluated as very low, if between 40-55, it is low, if between 55-70, it is medium, if between 70-85, it is high and if > 85, it is very high (Idowu et al., 2009).

The descriptive parameters of soil properties, minimum, maximum, mean, standard deviation, coefficient of variation, skewness and kurtosis values, were calculated with the help of Mini tab program (Mini tab 17). ArcGIS 10.5v program (Inverse Distance Weighting method power 2) was used in the creation of the soil quality distribution map.

Results And Discussion

The details provided in Table 2 are a statistical summary of soil properties, highlighting distribution patterns, variability, and overall soil quality. Most parameters, such as pH (skewness: -0.21) and clay content (skewness: 0.17), show near-normal distributions with minimal asymmetry and low kurtosis, indicating relatively symmetrical data without extreme tails. However, some variables deviate significantly from normality. For instance, phosphorus (skewness: 3.24, kurtosis: 10.81) and potassium (skewness: 1.25, kurtosis: 2.41) exhibit high skewness and kurtosis, pointing to positive skewness and heavy-tailed distributions with occasional outliers.

Variability, as indicated by the coefficient of variation (CV), is low for stable parameters like pH (CV: 9.88%) and physical quality score (CV: 9.96%), moderate for properties like clay content (CV: 36.05%), and high for nutrients like phosphorus (CV: 175%) and potassium (CV: 50.36%), reflecting significant fluctuations due to environmental or management factors. Biological quality scores (skewness: -2.46) are negatively skewed, with data concentrated at higher values, indicating strong soil health. Overall, the dataset reveals a mix of stable and highly variable parameters, emphasizing the importance of customized management strategies to account for the variability in soil conditions.

Table 2. Descriptive statistics of physical, chemical and biological properties and quality scores of soils.

Variable	Mean	StDev	Variance	CoefVar	Minimum	Maximum	Skewness	Kurtosis
EC (dS/m)	1.595	0.6494	0.4218	40.72	0.2652	2.91	-0.02	-0.64
pH	6.8833	0.6799	0.4622	9.88	5.27	8.05	-0.21	-1.1
Soil organic Carbon (%)	1.3459	0.5807	0.3372	43.15	0.1345	2.5552	0.05	-0.6
Clay (%)	38.86	14.01	196.22	36.05	6.18	70.08	0.17	-0.05
Silt (%)	19.562	6.665	44.421	34.07	2.443	36.188	-0.25	0.27
Sand (%)	41.58	18.06	326.13	43.43	7.39	85.62	0.13	-0.23
BD (g/cm^3)	1.4193	0.0892	0.008	6.29	1.25	1.58	-0.2	-0.83
Available water content	0.11722	0.02069	0.00043	17.65	0.05	0.19	-0.2	4.49
Agg.St (%)	58.15	14.46	209.06	24.86	15.55	84.74	-0.95	1.13
P (ppm)	29.39	51.43	2645.07	175	0.72	269.23	3.24	10.81
mgMBC/gsoil/24h	53.32	20.64	426	38.71	7.73	104.79	0.05	0.12
Sodium adsorption ratio	0.3128	0.1575	0.0248	50.36	0.0543	0.7936	1.25	2.41
K (ppm)	121.97	61.42	3772.84	50.36	21.19	309.5	1.25	2.41
Physical Quality Score	54.833	5.463	29.840	9.96	41.000	70.000	0.57	1.39
Chemical Quality Score	73.43	8.05	64.78	10.96	43.00	86.00	-0.94	2.44
Biological Quality Score	95.185	7.250	52.569	7.62	64.000	100.000	-2.46	6.72
Soil Quality Index	74.481	5.161	26.632	6.93	53.000	84.000	-1.68	4.84

According to the SMAF model soil quality scoring Table 3 The soil quality scores across different land use types Pasture, Forest, and Cultivated show distinct patterns in physical, chemical, and biological quality.

Pasture has the highest Chemical Quality Score (86), benefiting from organic matter recycling and nutrient cycling through grazing. However, its Physical Quality (53) is slightly lower due to potential compaction from grazing. Forest soils score well across all dimensions, with the highest Biological Quality Score (97) reflecting rich microbial activity and organic matter decomposition. Forests also have a strong Physical Quality (55), aided by minimal disturbance and natural processes. Cultivated land scores the highest in Physical Quality (56) due to intensive soil management practices but shows the lowest Chemical (78) and Biological (91) scores, likely due to the impacts of tillage, fertilizer use, and reduced soil biodiversity (Liu & Wang, 2019). Overall, forests exhibit the most balanced soil health (Amacher, O'Neil, & Perry, 2007) while cultivated lands need attention to chemical and biological quality for long-term sustainability. Pastures perform well in chemical health but may benefit from measures to prevent soil compaction.

Table 3. SMAF soil quality scores of land use types

Land use type	Physical Quality Score	Chemical Quality Score	Biological Quality Score
Pasture	53	86	95
Forest	55	83	97
Cultivated	56	78	91

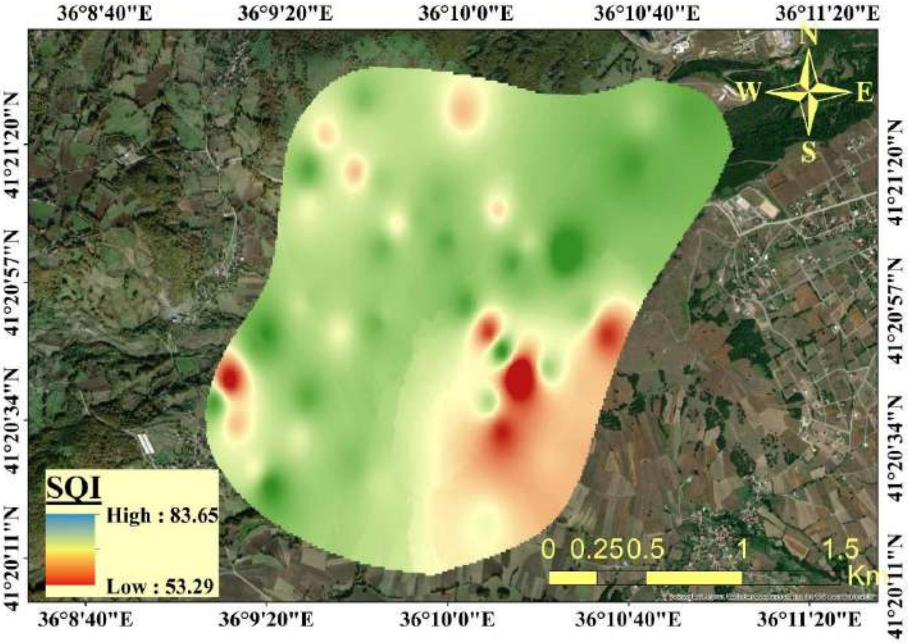


Figure 3.Soil quality distribution map of the study area

The soil quality distribution map reveals significant spatial variability in Soil Quality Index (SQI) values across the study area, ranging from 53.29 (low) to 83.65 (high). High-quality zones, depicted in green, are predominantly located in the northern and northeastern parts, indicating well-structured soils with favorable physical, chemical, and biological properties, likely due to minimal disturbance or optimal land use. In contrast, low-quality zones, shown in red, are concentrated in the southern and southeastern areas, potentially reflecting soil degradation caused by erosion, intensive land use, or reduced organic matter. The gradient from red to green suggests gradual transitions influenced by factors such as topography, drainage, and land management practices. This map underscores the need for site-specific soil management strategies, focusing on improving degraded zones while conserving the high-quality areas to ensure sustainable land use.

Conclusion

In this study, soil samples were collected from pasture, forest, and wheat-cultivated land areas in Aksu Village, Samsun, located along the southern coast of the Black Sea. A total of 54 soil samples were obtained from the study area, representing the three land use types, to evaluate soil quality using the Soil Management Assessment Framework (SMAF) model.

The soil quality assessment using the SMAF model revealed varied levels of soil quality across the study area, with strengths in chemical and biological properties but moderate limitations in physical attributes. The physical quality score was classified as medium (55), reflecting challenges such as low aggregate stability and low available water content, which suggest susceptibility to erosion and limited water retention, while bulk density was medium and water-filled pore space was high, indicating some compaction concerns but sufficient moisture levels. The chemical quality score was high (82), but individual indicators showed significant variability, with very high pH, plant-available potassium, and sodium adsorption ratio (SAR) raising concerns about nutrient imbalances and potential salinity issues, despite medium levels of soil organic carbon and plant-available phosphorus indicating room for fertility improvement. The biological quality score was very high (95), driven by robust microbial biomass carbon, reflecting strong microbial activity and nutrient cycling. Overall, the findings highlight the need for integrated management practices to address physical and chemical limitations while taking advantage of the high biological quality to promote sustainable soil health and productivity moreover these findings indicate that while the chemical and biological soil qualities are predominantly high to very high, the physical soil quality is a limiting factor in the study area. Efforts to improve physical indicators, such as aggregate stability and available water content, could enhance overall soil functionality and sustainability.

The general soil quality score of the study area was determined as high quality with 75. This high general soil quality score of 75 highlights the overall health and productivity of the study area's soils, emphasizing their potential to support sustainable land management and agricultural practices with targeted improvements in specific soil quality parameters.

Acknowledgments

This research was supported by Ondokuz Mayıs University under the project code PYO.ZRT.1914.23.002. The authors thank all contributors for their valuable support.

References

Amacher, M. C., O'Neil, K. P., & Perry, C. H. (2007). Soil vital signs: a new soil quality index (SQI) for assessing forest soil health. Res. Pap. RMRS-RP-65. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 12 p., 65.

Anderson, J. P., & Domsch, K. H. (1978). A physiological method for the quantitative measurement of microbial biomass in soils. Soil biology and biochemistry, 10(3), 215-221.

Andrews, S. S., & Carroll, C. R. (2001). Designing a soil quality assessment tool for sustainable agroecosystem management. Ecological Applications, 11(6), 1573-1585.

Andrews, S. S., Karlen, D. L., & Cambardella, C. A. (2004). The soil management assessment framework: a quantitative soil quality evaluation method. Soil Science Society of America Journal, 68(6), 1945-1962.

Bone, J., Head, M., Barraclough, D., Archer, M., Scheib, C., Flight, D., & Voulvoulis, N. (2010). Soil quality assessment under emerging regulatory requirements. Environment International, 36(6), 609-622.

Bouyoucos, G. J. (1951). A recalibration of the hydrometer method for making mechanical analysis of soils.

Burt, R. (1992). Soil survey laboratory methods manual: USDA.

Cherubin, M. R., Karlen, D. L., Franco, A. L., Cerri, C. E., Tormena, C. A., & Cerri, C. C. (2016). A Soil Management Assessment Framework (SMAF) evaluation of Brazilian sugarcane expansion on soil quality. Soil Science Society of America Journal, 80(1), 215-226.

Idowu, O., Van Es, H., Abawi, G., Wolfe, D., Schindelbeck, R., Moebius-Clune, B., & Gugino, B. (2009). Use of an integrative soil health test for evaluation of soil management impacts. Renewable agriculture and food systems, 24(3), 214-224.

Kacar, B. (1994). Bitki ve toprağın kimyasal analizleri: Ankara ÜnİVersitesi Ziraat Fakültesi Eğitim, Araştırma ve Geliştirme Vakfı.

Kalu, S., Koirala, M., Khadka, U. R., & Anup, K. (2015). Soil quality assessment for different land use in the Panchase area of western Nepal. International Journal of Environmental Protection, 5(1), 38-43.

Karlen, D. L., & Stott, D. E. (1994). A framework for evaluating physical and chemical indicators of soil quality. Defining soil quality for a sustainable environment, 35, 53-72.

Kemper, W. D., & Rosenau, R. C. (1986). Aggregate stability and size distribution. Methods of soil analysis: Part 1 Physical and mineralogical methods, 5, 425-442.

Klute, A. (1986). Water retention: laboratory methods. Methods of soil analysis: Part 1 Physical and mineralogical methods, 5, 635-662.

Liu, Z., & Wang, H. (2019). Soil Quality Analysis in Newly Increased Cultivated Land. Paper presented at the IOP Conference Series: Earth and Environmental Science.

Loch, R., & Rosewell, C. (1992). Laboratory methods for measurement of soil erodibilities (K-factors) for the universal soil loss equation. Soil Research, 30(2), 233-248.

Mulat, Y., Kibret, K., Bedadi, B., & Mohammed, M. (2021). Soil quality evaluation under different land use types in Kersa sub-watershed, eastern Ethiopia. Environmental Systems Research, 10, 1-11.

Nelson, D. W., & Sommers, L. E. (1982). Total carbon, organic carbon, and organic matter. Methods of soil analysis: Part 2 chemical and microbiological properties, 9, 539-579.

Pacci, S., Kaya, N. S., Dengiz, O., & Turan, I. D. (2021). Soil quality assessment using SMAF model in pasture land located in Van Basin.

Pachani, S., & Kashyap, N. (2020). Soil health and its quality: A Review. IJCS, 8(2), 1434-1436.

Palojärvi, A., & Nuutinen, V. (2002). The soil quality concept and its importance in the study of Finnish arable soils.

Patel, P., Rathwa, M., Patel, H., Patel, V., & Shiyal, V. (2022). Biochar: An Emerging Soil Amendment for Sustaining Soil Health and Black Gold for Indian Agriculture. Journal of Experimental Agriculture International, 44(12), 6-12.

Vezzani, F. M., & Mielniczuk, J. (2009). An overview of soil quality. Revista Brasileira de Ciência do Solo, 33, 743-755.

Zornoza, R., Acosta, J., Bastida, F., Domínguez, S., Toledo, D., & Faz, A. (2014). Identification of sensitive indicators to assess the interrelationship between soil quality, management practices and human health. Soil, 1(1), 463-495.

The role of Bacillus megaterium in promoting phosphorus availability and sustainable crop production

Prabesh RAI [1,2,*], Rıdvan KIZILKAYA [1]

[1] Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye
[2] Department of Plant Physiology, Biochemistry, and Genetics. Agricultural University – Plovdiv, Bulgaria

***Corresponding Author**

Prabesh RAI
prabeshwrai@gmail.com

Abstract

Phosphorus (P) is a vital macronutrient essential for plant growth and development, second only to nitrogen. It plays a central role in energy transfer, photosynthesis, and macromolecular biosynthesis. However, its availability in soil is often limited due to its fixation into insoluble forms, resulting in significant challenges for crop productivity and global food security. Traditional approaches to addressing phosphorus deficiency rely heavily on synthetic fertilizers derived from rock phosphate, a non-renewable resource expected to be depleted within the next century. Furthermore, the excessive use of chemical fertilizers has led to environmental issues, such as eutrophication, highlighting the need for sustainable alternatives. This review explores the role of Bacillus megaterium, a phosphate-solubilizing bacterium, as a promising solution for improving phosphorus bioavailability and promoting plant growth. B. megaterium enhances soil phosphorus availability through mechanisms such as the secretion of organic acids, enzymatic activities, and the release of inorganic compounds. Additionally, it acts as a plant growth promoter by producing phytohormones like auxins and gibberellins, which stimulate root development and nutrient uptake. Its application has demonstrated increased crop yields in various crops, including wheat, maize, and cucumber, while simultaneously improving soil structure, nutrient dynamics, and microbial diversity. While the potential of B. megaterium is evident, its efficacy varies across soil types, environmental conditions, and agricultural systems. Further research is required to optimize its application and integration into sustainable farming practices. This review underscores the ecological and agronomic importance of microbial solutions, such as B. megaterium, in reducing reliance on finite phosphorus resources and achieving sustainable agriculture.

Keywords: Bacillus megaterium, Phosphorus Solubilization, Sustainable Agriculture, Soil Nutrient Dynamics, Plant Growth Promotion, Phosphorus Fractionation

Introduction

Phosphorus (P) is a vital macronutrient that plays a crucial role in the growth and development of all crops. It is essential for various physiological processes, such as photosynthesis, energy transfer and macromolecular biosynthesis (Chouyia et al., 2022; Khan et al., 2010). Adequate phosphorus levels are crucial for developing roots, flowers, and seeds, with their concentration reaching up to 0.2% of a plant's dry weight (Alori et al., 2017; Azziz et al., 2012; Hufnagel et al., 2014). As the global population is projected to exceed 9.7 billion by 2050, increasing food production has become an urgent priority (Kumar et al., 2021). Wheat (Triticum aestivum L.), one of the world's most important staple crops, currently provides food for over 30% of the global population (Ali et al., 2012; Shi and Ling, 2018). Its productivity is closely tied to nutrient availability in the soil, particularly Phosphorus. The mechanisms regulating phosphorus availability are fundamental during the early stages of plant growth, as deficiencies during this period can significantly impact crop productivity compared to later stages (Aziz et al., 2014; Grant et al., 2001).

Although agricultural soils contain considerable amounts of total Phosphorus, only a tiny fraction is accessible to plants. The concentration of plant-available Phosphorus rarely exceeds 10 μM in most of the arable land (Bieleski L, 1973; Raymond et al., 2021; Suleimanova et al., 2015). P exists mainly in two forms in soil: Organic (30-65%), often locked in complex molecules, making it difficult for plants to access, and inorganic (35–70%), derived from minerals and synthetic fertilizers. It is highly reactive and often forms insoluble compounds with cations like Fe^{3+}, Al^{3+}, and Ca^{2+}, particularly in acidic and alkaline soils, which limits its availability to plants. It typically exists in two forms: soluble orthophosphates ($H_2PO_4^-$, HPO_4^{2-}), which are available for plant uptake, and insoluble phosphate compounds that are locked in the soil matrix. In acidic soils, Phosphorus reacts with iron and aluminum, forming insoluble iron and aluminum phosphates, while in alkaline soils, it precipitates as calcium phosphate, which is also unavailable to plants. This strong tendency for inorganic Phosphorus to bind with soil minerals means that most of the Phosphorus applied as fertilizer becomes "fixed" in forms that plants cannot use, further compounding the issue of phosphorus deficiency (Solangi et al., 2023; Suleimanova et al., 2015; Yan et al., 2024). The most common strategy for addressing phosphorus deficiency in agriculture has been continuous application of phosphorus fertilizer. However, modern agriculture heavily depends on chemical fertilizers derived from rock phosphate- a finite resource estimated to run out within 50-100 years, with the peak phosphor production anticipated around 2030 (Cordell and White, 2014; Granada et al., 2018). In addition, many environmental issues, such as eutrophication, have resulted due to excessive use of P fertilizers (Muntwyler et al., 2024; Roberts and Johnston, 2015). Therefore, finding alternatives to synthetic phosphorus fertilizers has become crucial in modern agriculture.

In the context of sustainable agriculture agricultural practices, inoculating microbes like Bacillus megaterium var phosphaticum have emerged promising solutions for enhancing nutrient viability like Phosphorus (Mohabeer et al., 1997; Zhao et al., 2021, 2019). Numerous studies have shown that B. megaterium, a gram-positive rod-shaped bacterium, can solubilize and mineralize phosphate via organic and inorganic acid release, phosphatase (de Oliveira-Paiva et al., 2024; Mohabeer et al., 1997). Apart from its roles in P solubilization, B. megaterium contributes to overall plant health by producing growth-stimulating substances such as auxins and gibberellins, which stimulate root growth and nutrient uptakes (Fasim et al., 2002). Optimum soil pH plays a critical role in the availability and solubilization of p. The pH range suitable for its solubility in the soil is between 6.0 and 7.5; outside this range, p remains insoluble, which is less available for plant absorption. Iron and aluminum are abundant in acidic pH soil, which reacts with Phosphorus, forming insoluble iron and aluminum phosphate. In contrast, in alkaline soil, it precipitates as calcium phosphate (Bai et al., 2024; Setiawati et al., 2022). Thus, pH plays a vital role in phosphorus availability in wheat cultivation.

With the global increase in food demand and finite resources of Phosphorus, there is a need for a sustainable solution. Microbial inoculants like Bacillus megaterium offer an alternative approach to solubilize insoluble phosphorus in soil and decrease reliance on synthetic fertilizers. This review aims to provide an in-depth analysis of Bacillus megaterium's role in P solubilization and its interaction with soil pH in wheat yield.

Inorganic Phosphorus Fractionation in Soils

P in the soil exists in two forms (organic and inorganic), and their availability is generally affected by soil P fractionation. Organic (Po) includes compounds such as phospholipid, nucleic acid, inositol phosphates which needs microbial activities to become available to the plants. In contrast, inorganic (Pi) includes calcium-bound (Ca-P), Iron bound (Fe-P) and Aluminum bound (Al-P) phosphates (Cross and Schlesinger, 1995; Jin et al., 2021). Various methods have been developed to fractionate P in different soil conditions and type, focusing on distinct aspect of P and its availability to crops. Among these, P fractionation method purposed by (Hedley et al., 1982) later was modified by (Tiessen and Moir, 2007) has been widely adopted. This method allows for comprehensive, quantitative evaluation of soil P fractions and transformation under different soil types, cropping systems, tillage practices and fertilization managements strategies (Jin et al., 2021).

Role of Bacillus megaterium in Phosphorus Solubilization

In 1935, soviet researcher Monkina successfully isolated Bacillus megaterium var. phosphaticum, known for its unique ability to solubilize insoluble forms of phosphorus into bioavailable forms that plant can utilize. Monkina then applied this bacterium to decompose organic phosphorus in soil, making beginning of studies on producing phosphorus solubilizing bacteria as a tool for improving soil P availability. B. megaterium promotes phosphorus release through several biochemical mechanisms, including organic acid production, enzymatic activities, and the release of inorganic compounds (Chouyia et al., 2022; Kang et al., 2014). Result from whole genomic mapping analysis of B. megaterium HT517 by (Saeid et al., 2018) found several functional genes in B. megaterium (pyk, aceB, pyc, ackA, gltA, buk, and aroK) responsible for organic acid secretion. Also, similar study on whole genome analysis of B. megaterium JX285 reported similar result with functional genes such as citrate synthase related to organic acid synthesis and the mechanism of its secretions to dissolve phosphorus.

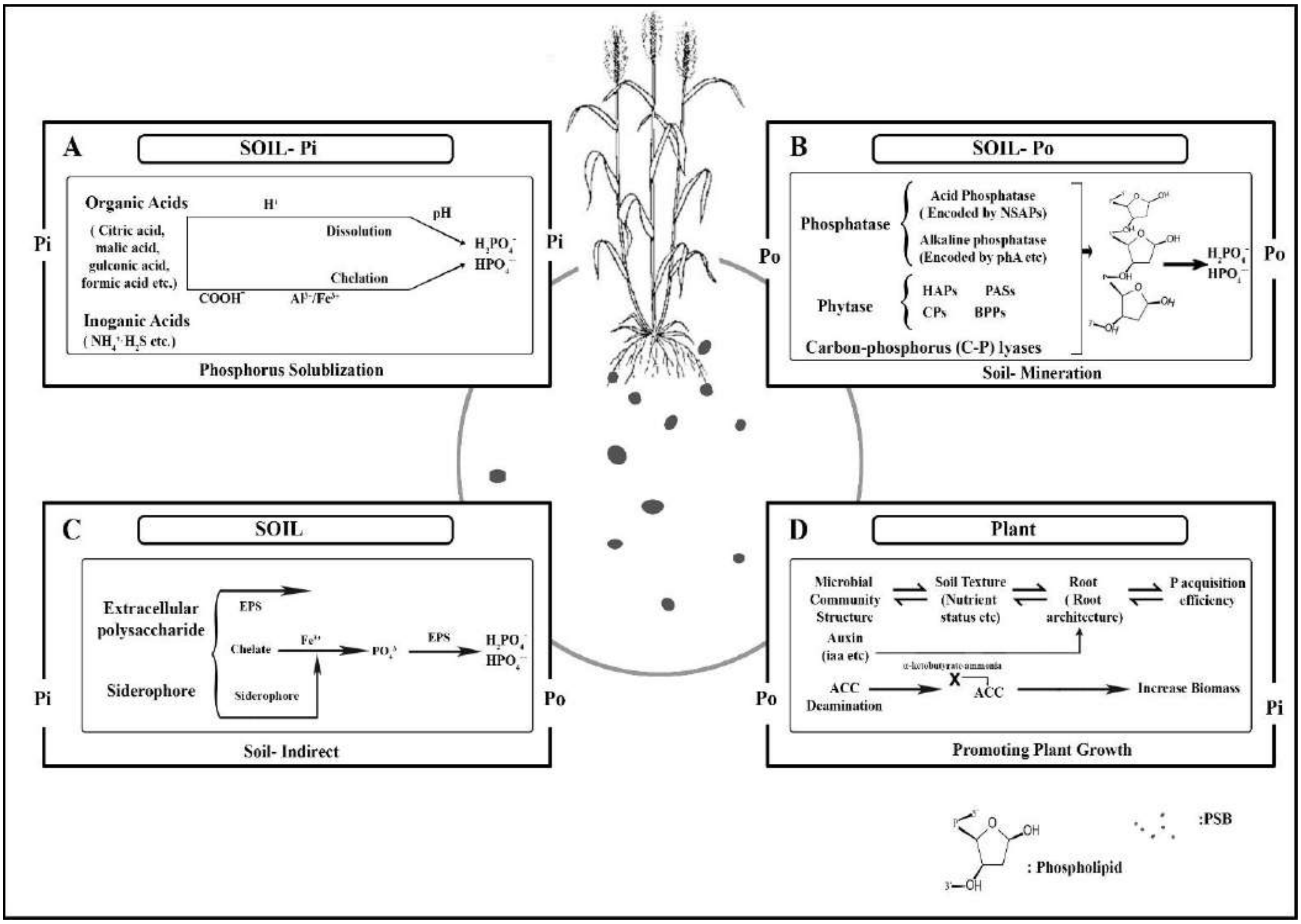


Figure 1: PSB mechanisms to solubilize and mineralize phosphate. Note: Panel A. Soil solubilizing mechanism of inorganic P in soils. Panel B. Soil mineralization mechanism of organic P in soils. Panel C. Indirect mechanism of PSB affecting P in soils. Panel D. Plant growth-promoting mechanism of PSB

Impact of Bacillus megaterium Inoculation on crop yield

Inoculation of B. megaterium has gained significant attention as a sustainable approach to enhance crop yield, particularly in the soil with limited p availability. Several studies have shown the positive impacts of B. megaterium inoculation on various crops, including Legume, Cereals, and vegetables. The study conducted by (Zhao et al., 2021) found that the application of B megaterium significantly improved cucumber yields by 11.8% to 15.2% compared to conventional fertilization alone. This enhancement was also reflected in the increased accumulation of phosphorus (P) and potassium (K) in both cucumber fruits and roots, with increases of 27.5% to 46.1% for P and 17.8% to 45.1% for K under the treatment with Bacillus megaterium. Similarly, (Sandeep et al., 2011), reported significant improvements in various growth parameters of Ayapana plants inoculated with Bacillus megaterium compared to uninoculated control plants. Inoculated plants exhibited greater height, a greater number of leaves, and increased in dry and fresh weighs of shoot and root. Another study by Kim et al. demonstrated that inoculation with Bacillus megaterium MJ1212 significantly enhanced growth parameters in mustard plants, including increased shoot and root lengths as well as higher fresh plant weight.

Table 1: Effects of B. megaterium Inoculation on Crops: Recent Research Findings

Crops	Effect of *Bacillus Megaterium* Inoculation	References
Maize	*B. megaterium* CNPMS B119 increases maize grain yield, with an average 22 % and 6% in Sete Lagoas and Santo Antônio de Goiás, respectively	de Oliveira-Paiva et al. (2024)
Wheat	The application of *Bacillus megaterium* DSM 3228 along with rock phosphate in calcareous soil significantly enhanced both grain and stem yields of wheat.	Bayraklı (2022)
Rice	Two Isolates of *B. megaterium* strain (CACC109 and CACC119) exhibits various, including phosphorus solubilization, indole-3-acetic acid production, siderophore secretion, 1-aminocyclopropane-1-carboxylate deaminase activity, and exopolysaccharide production.	Lee et al. (2024)
Black Gram	Two field experiments conducted over two years in low-pH soils demonstrated that the application of a *Bacillus megaterium* -fortified superphosphate-biochar formulation at a rate of 750 kg ha^{-1}resulted in significantly higher soil available phosphorus (9.7 mg kg^{-1}) and phosphorus uptake (15.1 kg ha^{-1}). This led to a 13% increase in phosphorus availability and a 24% increase in uptake compared to superphosphate alone.	Pandian et al. (2024)
Soyabean	The study suggests that the newly isolated strains of *Bacillus megaterium* can be effectively utilized in soybean bio-priming as either a single inoculant or in combination with other strains, which could enhance crop performance under various conditions.	Miljaković et al. (2022)
Cucumber	The application of *Bacillus megaterium* significantly enhanced cucumber yields by 11.8% to 15.2% compared to conventional fertilization alone. This increase was attributed to improved phosphorus (P) and potassium (K) accumulation in both cucumber fruits and roots, with increases of 27.5% to 46.1% for P and 17.8% to 45.1% for K.	Zhao et al. (2021)

Conclusion

Phosphorus (P) plays an important role in growth and development of plants but its availability is often limited due to its fixation in insoluble form. Chemical fertilizers have been widely used to address this issue. These synthetic fertilizers, however, poses significant environmental challenges including eutrophication. They also rely on finite rock phosphate reserves, which are rapidly depleting, highlighting the need for sustainable alternatives. B. megaterium has demonstrated its ability to solubilized mineral forms of phosphorus to pant available forms. It enhances soil nutrient accessibility through mechanisms like organic acid production, enzymatic activities and boost crop production. Its capacity to improve soil available P availability and promoting plant growth by producing growth-stimulating substances like auxins position it as a key component in sustainable agriculture. Utilization of such microbes can reduce dependency on finite P resources and support environmentally sustainable agriculture. Further research is required to optimize its use across different soil types and farming systems.

Acknowledgments

This research was conducted as part of the Erasmus Mundus Joint Master's Degree in Soil Science (emiSS) programme, funded by European Commission, which provided financial support for first author for the academic year 2023-2025. The author sincerely thanks the grateful to the European Commission for this invaluable opportunity.

References

Ali, A., Khaliq, T., Ahmad, A., Ahmad, S., Malik, A.U., Rasul, F., 2012. How wheat responses to nitrogen in the field? A review Crop and Environment 3:71–76.

Alori, E.T., Glick, B.R., Babalola, O.O., 2017. Microbial phosphorus solubilization and its potential for use in sustainable agriculture. Frontiers in Microbiology 8: 971. https://doi.org/10.3389/fmicb.2017.00971

Aziz, T., Finnegan, P.M., Lambers, H., Jost, R., 2014. Organ-specific phosphorus-allocation patterns and transcript profiles linked to phosphorus efficiency in two contrasting wheat genotypes. Plant, Cell & Environment 37: 943–960. https://doi.org/10.1111/pce.12210

Azziz, G., Bajsa, N., Haghjou, T., Taulé, C., Valverde, Á., Igual, J.M., Arias, A., 2012. Abundance, diversity and prospecting of culturable phosphate solubilizing bacteria on soils under crop-pasture rotations in a no-tillage regime in Uruguay. Applied Soil Ecology 61: 320–326. https://doi.org/10.1016/j.apsoil.2011.10.004

Bai, K., Wang, W., Zhang, J., Yao, P., Cai, C., Xie, Z., Luo, L., Li, T., Wang, Z., 2024. Effects of phosphorus - solubilizing bacteria and biochar application on phosphorus availability and tomato growth under phosphorus stress. BMC Biology 22:211. https://doi.org/10.1186/s12915-024-02011-y

Bayraklı, B., 2022. Effect of Bacillus megaterium var. phosphaticum applied together with rock phosphate on wheat yield and some soil properties in a calcareous soil. Eurasian Journal of Soil Science 11: 198–205. https://doi.org/10.18393/ejss.1057950

Bieleski L, 1973. Phosphate pools, phosphate transport, and phosphate availability. Annual Review of Plant Biology 24: 225–252. https://doi.org/10.1146/annurev.pp.24.060173.001301

Chouyia, F.E., Ventorino, V., Pepe, O., 2022. Diversity, mechanisms and beneficial features of phosphate-solubilizing Streptomyces in sustainable agriculture: A review. Frontiers in Plant Science 13:1035358. https://doi.org/10.3389/fpls.2022.1035358

Cordell, D., White, S., 2014. Life's bottleneck: Sustaining the world's phosphorus for a food secure future. Annual Review of Environment and Resources 39: 161–188. https://doi.org/10.1146/annurev-environ-010213-113300

Cross, A.F., Schlesinger, W.H., 1995. A literature review and evaluation of the. Hedley fractionation: Applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. Geoderma 64: 197–214. https://doi.org/10.1016/0016-7061(94)00023-4

de Oliveira-Paiva, C.A., Bini, D., de Sousa, S.M., Ribeiro, V.P., dos Santos, F.C., de Paula Lana, U.G., de Souza, F.F., Gomes, E.A., Marriel, I.E., 2024. Inoculation with Bacillus megaterium CNPMS B119 and Bacillus subtilis CNPMS B2084 improve P-acquisition and maize yield in Brazil. Frontiers in Microbiology 15:1426166. https://doi.org/10.3389/fmicb.2024.1426166

Fasim, F., Ahmed, N., Parsons, R., Gadd, G.M., 2002. Solubilization of zinc salts by a bacterium isolated from the air environment of a tannery. FEMS Microbiology Letters 213: 1–6. https://doi.org/10.1111/j.1574-6968.2002.tb11277.x

Granada, C.E., Passaglia, L.M.P., de Souza, E.M., Sperotto, R.A., 2018. Is phosphate solubilization the forgotten child of plant growth-promoting rhizobacteria? Frontiers in Microbiology 9: 2054. https://doi.org/10.3389/fmicb.2018.02054

Grant, C.A., Flaten, D.N., Tomasiewicz, D.J., Sheppard, S.C., 2001. The importance of early season phosphorus nutrition. Canadian Journal of Plant Science 81: 211–224. https://doi.org/10.4141/P00-093

Hedley, M.J., Stewart, J.W.B., Chauhan, B.S., 1982. Changes in Inorganic and Organic Soil Phosphorus Fractions Induced by Cultivation Practices and by Laboratory Incubations. Soil Science Society of America Journal 46: 970–976. https://doi.org/10.2136/sssaj1982.03615995004600050017x

Hufnagel, B., de Sousa, S.M., Assis, L., Guimaraes, C.T., Leiser, W., Azevedo, G.C., Negri, B., Larson, B.G., Shaff, J.E., Pastina, M.M., Barros, B.A., Weltzien, E., Rattunde, H.F.W., Viana, J.H., Clark, R.T., Falcão, A., Gazaffi, R., Garcia, A.A.F., Schaffert, R.E., Kochian, L. V., Magalhaes, J. V., 2014. Duplicate and conquer: Multiple homologs of PHOSPHORUS-STARVATION TOLERANCE1 enhance phosphorus acquisition and sorghum performance on low-phosphorus soils. Plant Physiology 166: 659–677. https://doi.org/10.1104/pp.114.243949

Jin, X., Hu, C., Khan, A., Zhang, S., Yang, X., Jia, L., Sun, R., 2021. Comparison of fractionation methods for soil phosphorus with soils subjected to various long-term fertilization regimes on a calcareous soil. PeerJ Inorganic Chemistry 3: e3. https://doi.org/10.7717/peerj-ichem.3

Kang, S.M., Radhakrishnan, R., You, Y.H., Joo, G.J., Lee, I.J., Lee, K.E., Kim, J.H., 2014. Phosphate Solubilizing Bacillus megaterium mj1212 Regulates Endogenous Plant Carbohydrates and Amino Acids Contents to Promote Mustard Plant Growth. Indian Journal of Microbiology 54: 427–433. https://doi.org/10.1007/s12088-014-0476-6

Khan, M.S., Zaidi, A., Ahemad, M., Oves, M., Wani, P.A., 2010. Plant growth promotion by phosphate solubilizing fungi - Current perspective. Archives of Agronomy and Soil Science 56: 73–98. https://doi.org/10.1080/03650340902806469

Kumar, L., Chhogyel, N., Gopalakrishnan, T., Hasan, M.K., Jayasinghe, S.L., Kariyawasam, C.S., Kogo, B.K., Ratnayake, S., 2021. Climate change and future of agri-food production, In: Future Foods: Global Trends, Opportunities, and Sustainability Challenges. Bhot, R. (Ed.). Elsevier Inc. pp.49-79. https://doi.org/10.1016/B978-0-323-91001-9.00009-8

Lee, S., Kim, J.A., Song, J., Choe, S., Jang, G., Kim, Y., 2024. Plant growth-promoting rhizobacterium Bacillus megaterium modulates the expression of antioxidant-related and drought-responsive genes to protect rice (Oryza sativa L.) from drought. Frontiers in Microbiology 15:1430546. https://doi.org/10.3389/fmicb.2024.1430546

Miljaković, D., Marinković, J., Tamindžić, G., Đorđević, V., Tintor, B., Milošević, D., Ignjatov, M., Nikolić, Z., 2022. Bio-Priming of Soybean with Bradyrhizobium japonicum and Bacillus megaterium: Strategy to Improve Seed Germination and the Initial Seedling Growth. Plants 11(15): 1927. https://doi.org/10.3390/plants11151927

Mohabeer, A.J., Kaplan, P.J., Southern, J., Gander, R.M., 1997. Algaemia due to Prototheca wickerhamii in a patient with myasthenia gravis. Journal of Clinical Microbiology 35: 3305–3307. https://doi.org/10.1128/jcm.35.12.3305-3307.1997

Muntwyler, A., Panagos, P., Pfister, S., Lugato, E., 2024. Assessing the phosphorus cycle in European agricultural soils: Looking beyond current national phosphorus budgets. Science of The Total Environment 906: 167143. https://doi.org/10.1016/j.scitotenv.2023.167143

Pandian, K., Samiyappan, K., Rangasamy, A., Raju, I., Chitraputhirapillai, S., Bose, J., 2024. Bacillus megaterium-Embedded Organo Biochar Phosphorous Fertilizer Improves Soil Microbiome and Nutrient Availability to Enhance Black Gram (Vigna mungo L) Growth and Yield. Journal of Soil Science and Plant Nutrition 24: 2048–2063. https://doi.org/10.1007/s42729-024-01715-y

Raymond, N.S., Gómez-Muñoz, B., van der Bom, F.J.T., Nybroe, O., Jensen, L.S., Müller-Stöver, D.S., Oberson, A., Richardson, A.E., 2021. Phosphate-solubilising microorganisms for improved crop productivity: a critical assessment. New Phytologist 229: 1268–1277. https://doi.org/10.1111/nph.16924

Roberts, T.L., Johnston, A.E., 2015. Phosphorus use efficiency and management in agriculture. Resources, Conservation and Recycling 105: 275–281. https://doi.org/10.1016/j.resconrec.2015.09.013

Saeid, A., Prochownik, E., Dobrowolska-Iwanek, J., 2018. Phosphorus solubilization by Bacillus species. Molecules 23(11), 2897. https://doi.org/10.3390/molecules23112897

Sandeep, C., Tejus, M.S., Sanjeev, P., Tejaswini, G., Raman, R. V, Radhika, M., Suresh, C.K., Mulla, S.R., 2011. Growth response of Ayapana on inoculation with Bacillus megaterium isolated from different soil types of various agroclimatic zones of Karnataka. Journal of Phytology 3: 13–18.

Setiawati, T.C., Erwin, D., Mandala, M., Hidayatulah, A., 2022. Use of Bacillus as a Plant Growth-Promoting Rhizobacteria to Improve Phosphate and Potassium Availability in Acidic and Saline Soils. KnE Life Sciences pp.541–558. https://doi.org/10.18502/kls.v7i3.11160

Shi, X., Ling, H.Q., 2018. Current advances in genome sequencing of common wheat and its ancestral species. The Crop Journal 6: 15–21. https://doi.org/10.1016/j.cj.2017.11.001

Solangi, F., Zhu, X., Khan, S., Rais, N., Majeed, A., Sabir, M.A., Iqbal, R., Ali, S., Hafeez, A., Ali, B., Ercisli, S., Kayabasi, E.T., 2023. The Global Dilemma of Soil Legacy Phosphorus and Its Improvement Strategies under Recent Changes in Agro-Ecosystem Sustainability. ACS Omega 8: 23271–23282. https://doi.org/10.1021/acsomega.3c00823

Suleimanova, A.D., Beinhauer, A., Valeeva, L.R., Chastukhina, I.B., Balaban, N.P., Shakirov, E. V., Greiner, R., Sharipova, M.R., 2015. Novel glucose-1-phosphatase with high phytase activity and unusual metal ion activation from soil bacterium Pantoea sp. strain 3.5.1. Applied and Environmental Microbiology 81: 6790–6799. https://doi.org/10.1128/AEM.01384-15

Tiessen, H., Moir, J., 2007. Characterization of Available P by Sequential Extraction. In: Soil Sampling and Methods of Analysis. Carter, M.R., Gregorich, E.G. (Eds.). Lewis Publishers, Boca Raton, pp. 75-86.

Yan, W., Rao, W., Zheng, F., Wang, Y., Zhang, C., Li, T., 2024. Distribution and Transformation of Soil Phosphorus Forms under Different Land Use Patterns in an Urban Area of the Lower Yangtze River Basin, South China. Sustainability 16(5): 2142. https://doi.org/10.3390/su16052142

Zhao, Y., Mao, X., Zhang, M., Yang, W., Di, H.J., Ma, L., Liu, W., Li, B., 2021. The application of Bacillus Megaterium alters soil microbial community composition, bioavailability of soil phosphorus and potassium, and cucumber growth in the plastic shed system of North China. Agriculture, Ecosystems & Environment 307: 107236. https://doi.org/10.1016/j.agee.2020.107236

Zhao, Y., Zhang, M., Yang, W., Di, H.J., Ma, L., Liu, W., Li, B., 2019. Effects of microbial inoculants on phosphorus and potassium availability, bacterial community composition, and chili pepper growth in a calcareous soil: a greenhouse study. Journal of Soils and Sediments 19: 3597–3607. https://doi.org/10.1007/s11368-019-02319-1

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

Composted crop residues as organic amendments for soil and plant health

Shova AKTER [1,2,*], Rıdvan KIZILKAYA [1]

[1] Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye
[2] University of Agriculture in Krakow, Department of Soil Science and Soil Protection; Kraków, Poland

***Corresponding Author**

Shova AKTER

shova18akter@gmail.com

Abstract

Crop residues, the post-harvest remnants of agricultural crops, are valuable natural resources with significant potential for sustainable agricultural practices. Crop residues are mainly compromised of cellulose, hemicellulose, lignin, organic carbon (OC), and essential nutrients like nitrogen (N), phosphorus (P), and potassium (K), hence serve as an excellent source for organic fertilizer production. However, improper disposal methods, such as open-field burning, are widely practiced, leading to environmental pollution, greenhouse gas emissions, and the loss of valuable organic matter and nutrients. Composting emerges as a cost-effective and environmentally friendly technique for managing crop residues. Through microbial decomposition, composting transforms crop residues into nutrient-rich organic matter while eliminating harmful pathogens, odor, and unwanted materials. Unlike other residue management methods, composting enhances soil structure, nutrient cycling, and microbial biodiversity, thereby improving soil fertility and promoting sustainable crop production. Additionally, composted residues can address challenges in intensive agricultural systems, such as declining soil organic matter (SOM), soil degradation, and nutrient depletion. This review explores the composition of various crop residues and their nutrient profiles, emphasizing their potential to serve as organic amendments. It highlights the composting process as a critical tool for residue management, detailing its benefits for soil physiochemical and biological properties. Furthermore, the contribution of composted crop residues to improving plant productivity and addressing sustainability challenges in modern agriculture is discussed. By integrating crop residue composting into agricultural practices, a balanced and sustainable ecosystem can be achieved, benefiting both soil health and crop yields. This review aims to provide insights into the effective utilization of composted crop residues as a sustainable alternative to synthetic fertilizers, underscoring their role in enhancing soil quality and supporting eco-friendly agricultural practices.

Keywords: Composting, Crop residues, Physiochemical properties, Biological properties, Plant growth improvement, Organic amendments, Sustainable agriculture

Introduction

Crop residues, the remains of plant parts after harvesting, are a significant byproduct of agricultural production. With the rising global food demand and intensive farming practices, crop residue production has expanded drastically, increasing over threefold from 1589 Mt in 1960–61 to 5280 Mt in 2020–21 (Shinde et al., 2022). Annually, more than 5 billion megagrams of agricultural residues are generated worldwide, primarily from crops like wheat, maize, rice, sugarcane, soybean, and barley, which account for over 85% of global crop residue production (FAO, 2021).

Crop residues mainly consist of cellulose, hemicellulose, and lignin, along with trace amounts of nitrogen compounds, pectin, and mineral residues (Andlar et al., 2018). However, the lignin-hemicellulose matrix, lignin's hydrophobic properties, and cellulose's crystallinity make lignocellulosic biomass resistant to microbial enzyme degradation (Zheng et al., 2014). This resistance complicates their effective utilization, leading many farmers to burn residues in the field. This practice not only emits greenhouse gases (GHGs) but also hinders nutrient recycling and damages soil microbial communities through excessive heat and carbon release (Porichha et al., 2021; Shinde et al., 2022). Despite these challenges, crop residues are rich in nutrients and can serve as a critical source of soil organic carbon (SOC) (Schomberg et al., 1994). When returned to the soil, they can improve soil quality by increasing soil organic matter (SOM), enhancing soil structure, boosting microbial biomass, and supporting enzymatic activities (Zhao et al., 2016). This makes the incorporation of crop residues a promising strategy to address soil fertility loss and enhance global crop production.

Appropriate and eco-friendly management of crop residues is crucial for recycling organic matter and preserving agricultural sustainability. Methods such as in situ incorporation, surface retention, and ex situ composting allow for the effective use of these residues. Among these, ex situ composting is particularly advantageous as it involves collecting and composting residues alone or with farmyard manure to produce nutrient-rich manure. This compost can then be returned to the fields, completing the nutrient cycle. Composting is an economical, environmentally friendly method for converting agricultural biomass into high-quality organic amendments for crop production (Maniadakis et al., 2004). In addition to reducing biomass disposal issues, composting provides farmers with a self-sustaining source of fertilizer (Pane et al., 2015). This review explores the potential of composted crop residues in enhancing soil quality and promoting plant growth. It also identifies existing research gaps and suggests future directions to optimize crop residue management for sustainable agriculture.

Chemical Composition and Nutrient Dynamics of Crop Residues

Crop residues consist primarily of cellulose (25–50%), hemicellulose (15–35%), and lignin (8–30%) (Table 1), along with smaller quantities of proteins, soluble carbohydrates, and mineral nutrients (Fu et al., 2021). The exact composition varies significantly across plant species, influencing their decomposition rates and nutrient release dynamics. For instance, maize and wheat residues contain higher cellulose levels, while rice straw has relatively higher lignin content, making it more resistant to microbial breakdown (Zheng et al., 2014).

Table 1. Percentage Composition of Cellulose, Hemicellulose, and Lignin in Different Crop Residues

Crop residue	Cellulose %	Hemicellulose %	Lignin %	Reference
Maize straw	42.6	21.3	8.2	(Sarkar et al., 2012)
Rice straw	38.6-40.5	19.7- 29	18.5	(Sharma and Arora, 2011)
Wheat straw	30-39.2	26.1-50	14-21	(Sun et al., 1998; Chandra et al., 2012)
Barly straw	37.6	34.9	15.8	(Sun and Sun, 2002)
Soybean hull	33.49	17.15	9.88	(Brijwani et al., 2010)
Oats	26.6	21.3	24.8	(Claye et al., 1996)
Rye	26	16	13	(Bledzki et al., 2010)

In addition to their organic composition, crop residues are nutrient-rich, serving as an essential source of carbon (40–45%), potassium (14–23%), nitrogen (0.6–1%), and phosphorus (0.45–2%) (Wang et al., 2020). As shown in Table 2, the nutrient content of residues varies among crops, with maize having the highest carbon percentage, while soybean residues contain more nitrogen. This variability underscores the importance of crop-specific management practices.

Table 2. Nutrient Contents (C, N, P_2O_5, and K_2O) in Various Crop Residues (Fu et al., 2021; Shinde et al., 2022)

Crop residue	C%	N%	P_2O_5%	K_2O%
Wheat straw	42.1	0.48-0.60	0.16	1.18
Rice straw	40.74	0.61-0.79	0.18	1.38
Maize stover	43.86	0.52-1	0.18	1.35
Rapeseed stalk	42.93	0.70-0.77	0.22	1.14
Soyabean	40	0.88	0.14	0.65
Cotton stalk	45.83	0.40	0.10	0.66

The C/N ratio of residues plays a crucial role in their decomposition. Residues with a C/N ratio above 40 decompose more slowly, potentially immobilizing nitrogen in the soil, whereas a ratio of 35–40 is considered ideal for microbial activity (Singh et al., 2020). The nutrient release dynamics also depend on environmental conditions, such as soil type, climate, and residue management methods (Grzyb et al., 2020). For example, residues with higher lignin and cellulose content tend to mineralize more slowly, requiring external inputs to enhance decomposition (Baldock, 2007).

Composted Crop Residues as Fertilizer

Crop residues, when returned to the field, can provide substantial benefits to the agricultural ecosystem by recycling nutrients and enhancing soil fertility. However, their direct application is subject to ongoing debate due to variations in decomposition rates and potential negative effects. For instance, slower decomposition of straw can hinder the rooting of subsequent crops, while the organic acids released during this process may harm crop roots (Ren JiQin et al., 2019). To mitigate these issues, composting has emerged as a practical and effective solution for utilizing crop residues as organic fertilizers (Mengqi et al., 2023). Composting is a biological process that transforms agricultural residues into nutrient-rich organic amendments through controlled aerobic decomposition or fermentation. Unlike direct residue application, composting reduces the need for equipment and infrastructure, making it an economical choice for farmers (Porichha et al., 2021). However, the high lignocellulosic content of residues, composed of cellulose, hemicellulose, and lignin, slows down their natural degradation. To accelerate composting, lignocellulose-degrading microbial inoculants are often applied. For example, Kaur et al. (2019) demonstrated that combining rice straw with fungal cultures, rice bran, and fruit waste reduced the decomposition period to just 28 days, producing a biofertilizer rich in carbon and crude protein. Regular turning of the biomass during composting further improves aeration, enhances microbial activity, and accelerates the process (MA, 2004). During composting, microorganisms decompose organic materials, releasing essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K). The process also reduces the weight, volume, and water content of the residues, while suppressing pathogenic organisms (Külcü and Yaldiz, 2014). Composting increases the humic acid content of the material and eliminates harmful bacteria, weed seeds, and insect eggs, thus enhancing the overall quality of the resulting organic fertilizer. The application of composted crop residues offers numerous advantages for soil health and plant growth. These residues not only provide essential nutrients but also improve soil structure, enhance microbial activity, and boost water retention capacity. Furthermore, composting significantly reduces the environmental impact of residue burning, lowering greenhouse gas emissions and promoting sustainable farming practices. As a result, composted residues serve as an effective alternative to synthetic fertilizers, reducing farmers' reliance on chemical inputs and contributing to long-term soil fertility and productivity (Nkwachukwu et al., 2013).

Composted Crop Residues in Soil Quality Improvement

Effects on Physicochemical Properties

The application of composted crop residues has been extensively shown to improve the physicochemical properties of soil. Multiple studies have reported enhancements in total porosity, soil water content, potassium (K) and phosphorus (P) levels, aggregate stability, cation exchange capacity (CEC), and soil permeability (Aggarwal and Power, 1997; Li et al., 2021). Total soil porosity, a critical indicator of soil fertility and productivity, was observed to increase when straw compost was applied in combination with biochar (Barus, 2016). A long-term field experiment conducted in paddy fields of Northeast China revealed a 21.7% increase in total soil porosity after the application of 4500 kg ha^{-1} straw annually for five years (Zheng et al., 2019). The incorporation of composted plant residues enhances soil microbial activity, which in turn promotes the formation of larger aggregates and improves soil structural stability (Fu et al., 2021). The degree of structural stability varies depending on the type of crop residue applied. For example, soils treated with composted residues containing a higher proportion of humic acids exhibit significantly improved aggregate stability (Tejada et al., 2009).

Crop residues also have significant effects on soil pH, particularly in soils with low buffering capacity. For instance, a study by Cao et al. (2022) showed that rotary tillage combined with straw covering under no-till conditions reduced soil pH from 7.7 to 7.2. Conversely, other studies have reported increases in pH after crop residue incorporation, highlighting the variability of outcomes depending on soil types and residue composition (Butterly et al., 2013). Additionally, the accumulation of soil organic matter (SOM) from crop residues contributes to higher negative charges in the soil, thereby improving soil CEC. In a wheat–gourd rotation experiment, CEC of topsoil was found to increase by 9.39–21.59% with wheat straw incorporation over five cropping seasons (Rezig et al., 2013). Furthermore, the application of straw compost has been shown to enhance the availability of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K). Decomposing residues play a pivotal role in the nutrient cycle. For instance, Zhao et al. (2019) reported a 64% increase in available nitrogen after the addition of straw with partial fertilization. The decomposition process also releases ionic potassium, contributing to its accumulation in the soil. In a study by Yadav et al. (2021), the return of 90% (7.0 t) of soybean residues to the soil added 89.7 kg of potassium per hectare. Moreover, composted crop residues can contribute to soil quality improvement and even soil contamination remediation by reducing the bioavailability and mobility of heavy metals. For example, a greenhouse experiment showed that rice straw application at a 2% rate decreased nickel (Ni) bioavailability by 68% (Ali et al., 2020). Similarly, Xu Ping et al. (2016) found that a 1% (w/w) rice straw treatment reduced lead (Pb) concentrations in soil and maize shoots by 13.5% and 58.2%, respectively.

Biological properties improvement

Composted crop residues also play a vital role in enhancing the biological properties of soil. They serve as a renewable carbon source, mitigating the gradual loss of soil organic matter caused by intensive farming practices such as frequent tillage, continuous cropping, and excessive use of chemical fertilizers. For instance, the application of 5% (w/w) raw garlic stem increased soil organic carbon (SOC) by 50% (Ali et al., 2020). Incorporating crop residues as compost reduces the loss of organic carbon from the soil, while simultaneously creating a favorable environment for microbial growth and activity (Chen et al., 2016). The retention of crop residues enhances soil microbial diversity and abundance. A study by Zhang et al. (2021) found that sugarcane straw retention increased the abundance and diversity of fungal species in the topsoil (0–10 cm). Numerous studies have demonstrated that organic amendments stimulate the secretion of enzymes essential for nutrient cycling, such as urease, β-glucosidase, and alkaline phosphatase (Tejada et al., 2009). These enzymes are sensitive indicators of soil biological changes, as they respond more rapidly to modifications in soil management than physical or chemical factors (Bandick, 1999). The combined application of composted red clover (Trifolium pratense L.) and rapeseed (Brassica napus L.) residues has been shown to improve soil biological properties, including biomass carbon and enzymatic activities (Tejada et al., 2009). However, the quantity and quality of organic inputs play a critical role in determining microbial biomass carbon (MBC) and soil respiration rates. Higher soil respiration and MBC were observed in soils amended with residues containing high concentrations of fulvic acids, attributed to the higher labile proportion of organic matter in such residues (Tejada et al., 2009). Additionally, the application of various organic wastes, such as beet vinasse and cotton gin compost, has been shown to enhance enzyme activities such as urease, β-glucosidase, and alkaline phosphatase, further promoting nutrient cycling (Tejada and Gonzalez, 2006). Pane et al. (2015) documented improvements in soil biological activities, including basal respiration, β-glucosidase, dehydrogenase, alkaline phosphatase, arylsulphatase, and fluorescein diacetate hydrolysis, following the application of tomato-based composts.

Plant Productivity with Composted Plant Residues Incorporation

Composted crop residues play a vital role in enhancing plant growth and productivity by improving nutrient acquisition and stimulating biological processes in the soil. Several studies have demonstrated the positive effects of composted plant residues on various crops and their yields. For instance, a four-year study conducted in Xelloric Calciorthid soils in the Guadalquivir Valley, Andalusia, showed that the application of composts derived from red clover and rapeseed residues significantly enhanced spontaneous vegetation growth compared to untreated soils (Tejada et al., 2009). This highlights the potential of composted residues to restore soil fertility and promote natural vegetation growth in degraded soils. Similarly, Hussein et al. (2022) documented the beneficial effects of rice and soybean straw compost incorporation on wheat yield components, including an increase in spike number, spike length, spike weight, 100-grain weight, grain yield, and straw yield. This study underscores the role of composted residues in improving both qualitative and quantitative aspects of crop production. The application of crop residue-based composts from chickpea stover, pigeon pea stover, and mustard stover has also been shown to significantly enhance grain and straw yields of rice (Dadhich et al., 2012). Furthermore, the incorporation of rice straw compost at a rate of 5 t/ha, along with half of the recommended dose of inorganic fertilizer, resulted in improved grain and straw yields of rice. This finding, reported by Goyal et al. (2009), highlights the complementary role of composted residues when used in combination with chemical fertilizers, reducing dependency on inorganic inputs while maintaining high productivity. In addition to improving yields, composted residues also contribute to plant health. For example, microbial-infused rice straw compost was found to increase seed germination rates, enhance plant growth, and suppress the growth of Sclerotium rolfsii, a pathogen causing foot rot in chili plants (Kausar et al., 2014). This demonstrates the potential of enriched composts in integrated pest and disease management, further adding to their value as sustainable agricultural inputs.

Conclusion

Returning crop residues to agricultural fields is a vital strategy for enhancing soil health and fostering sustainable agricultural practices. However, the improper application of straw return techniques, often employed by farmers, can lead to several adverse effects, including reduced soil fertility, decreased crop productivity, and challenges in maintaining sustainable yields. This underscores the necessity of adopting proper techniques, with composting emerging as a highly effective and promising solution. Composting of crop residues not only improves plant growth conditions but also restores soil quality by delivering multiple ecosystem services. These include enhancing nutrient availability for plants, increasing soil microbial activity and biodiversity, replenishing soil carbon reserves, and reinstating the soil's natural suppressive properties against pathogens. Furthermore, composted residues serve as a natural and organic fertilizer, offering an agronomically viable and environmentally friendly alternative to synthetic fertilizers. Despite its benefits, the efficiency and quality of composted residues can be further optimized through the development of advanced machinery and innovative composting techniques. Such improvements are essential for ensuring the holistic application of composted residues in modern agricultural systems, addressing the dual goals of productivity and sustainability. Future research and technological advancements should focus on improving the composting process, tailoring it to various crop residues and soil types, and scaling its application to meet the growing demands of sustainable agriculture.

References

Aggarwal, R.K., Power, J.F., 1997. Use of crop residue and manure to conserve water and enhance nutrient availability and pearl millet yields in an arid tropical region. Soil and Tillage Research 41:43-51.

Ali, A., Ghani, M. I., Haiyan, D., Iqbal, M., Cheng, Z., and Cai, Z., 2020. Garlic substrate induces cucumber growth development and decreases Fusarium wilt through regulation of soil microbial community structure and diversity in replanted disturbed soil. International Journal of Molecular Sciences 21: 6008.

Ali, U., Shaaban, M., Bashir, S., Fu, Q., Zhu, J., Islam, M. S., Hu, H., 2020. Effect of rice straw, biochar and calcite on maize plant and Ni bio-availability in acidic Ni contaminated soil. Journal of Environmental Management 259: 109674.

Andlar, M., Rezić, T., Marđetko, N., Kracher, D., Ludwig, R., Šantek, B., 2018. Lignocellulose degradation: An overview of fungi and fungal enzymes involved in lignocellulose degradation. Engineering in Life Sciences 18:768–778.

Baldock, J.A., 2007. Composition and cycling of organic carbon in soil. In: Nutrient cycling in terrestrial ecosystems (pp. 1-35). Berlin, Heidelberg: Springer Berlin Heidelberg.

Bandick, AK., 1999. Field management effects on soil enzyme activities. Soil Biology and Biochemistry 31: 1471-1479.

Barus, J., 2016. Utilization of crops residues as compost and biochar for improving soil physical properties and upland rice productivity. Journal of Degraded and Mining Lands Management 3: 631.

Bledzki, A. K., Mamun, A. A., and Volk, J., 2010. Physical, chemical and surface properties of wheat husk, rye husk and soft wood and their polypropylene composites. Composites Part A: Applied Science and Manufacturing 41: 480–488.

Brijwani, K., Oberoi, H. S., Vadlani, P. V., 2010. Production of a cellulolytic enzyme system in mixed-culture solid-state fermentation of soybean hulls supplemented with wheat bran. Process Biochemistry 45: 120–128.

Butterly, C. R., Baldock, J. A., Tang, C., 2013. The contribution of crop residues to changes in soil pH under field conditions. Plant and Soil 366: 185–198.

Cao, Q., Li, G., Yang, F., Kong, F., Cui, Z., Jiang, X., Lu, Y., Zhang, E., 2022. Eleven-year mulching and tillage practices alter the soil quality and bacterial community composition in Northeast China. Archives of Agronomy and Soil Science 68:1274–1289.

Chandra, R., Takeuchi, H., Hasegawa, T., 2012. Methane production from lignocellulosic agricultural crop wastes: A review in context to second generation of biofuel production. Renewable and Sustainable Energy Reviews 16: 1462–1476.

Chen, S., Xu, C., Yan, J., Zhang, X., Zhang, X., Wang, D., 2016. The influence of the type of crop residue on soil organic carbon fractions: An 11-year field study of rice-based cropping systems in southeast China. Agriculture, Ecosystems & Environment 223: 261–269.

Claye, S. S., Idouraine, A., Weber, C. W., 1996. Extraction and fractionation of insoluble fiber from five fiber sources. Food Chemistry 57:305–310.

Dadhich, S. K., Pandey, A. K., Prasanna, R., Nain, L., Kaushik, B. D., 2012. Optimizing crop residue-based composts for enhancing soil fertility and crop yield of rice. The Indian Journal of Agricultural Sciences 82:85–88.

FAO., 2021. FAOSTAT. URL http://www.fao.org/faostat/en/#data/ QC (Accessed 12 Nov 2024).

Fu, B., Chen, L., Huang, H., Qu, P., Wei, Z., 2021. Impacts of crop residues on soil health: A review. Environmental Pollutants and Bioavailability 33:164–173.

Goyal, S., Singh, D., Suneja, S., Kapoor, K. K., 2009. Effect of rice straw compost on soil microbiological properties and yield of rice. Indian Journal of Agricultural Research 43: 263–268.

Grzyb, A., Wolna-Maruwka, A., Niewiadomska, A., 2020. Environmental factors affecting the mineralization of crop residues. Agronomy 10: 1951.

Hussein, M., Ali, M., Abbas, M. H. H., Bassoon, M. A., 2022. Composting Animal and Plant Residues for Improving the Characteristics of a Clayey Soil and Enhancing the Productivity of Wheat Plant Grown Thereon. Egyptian Journal of Soil Science 62: 195–208.

Kaur, P., Singh Kocher, G., Sachdeva Taggar, M., 2019. Enhanced bio-composting of rice straw using agricultural residues: An alternate to burning. International Journal of Recycling of Organic Waste in Agriculture 8: 479–483.

Kausar, H., Razi Ismail, M., Saud, H. M., Othman, R., Habib, S. H., Siddiqui, Y., 2014. Bio-Efficacy of Microbial Infused Rice Straw Compost on Plant Growth Promotion and Induction of Disease Resistance in Chili. Compost Science & Utilization 22: 1–10.
Külcü, R., Yaldiz, O., 2014. The composting of agricultural wastes and the new parameter for the assessment of the process. Ecological Engineering 69: 220–225.
Li, J., Ye, X., Zhang, Y., Chen, J., Yu, N., Zou, H., 2021. Maize straw deep-burying promotes soil bacteria community abundance and improves soil fertility. Journal of Soil Science and Plant Nutrition 21: 1397–1407.
MA, G.-T., 2004. Ecological organic fertilizers and sustainable development of agriculture. Chinese Journal of Eco-Agriculture 12: 191–193.
Maniadakis, K., Lasaridi, K., Manios, Y., Kyriacou, M., Manios, T., 2004. Integrated Waste Management Through Producers and Consumers Education: Composting of Vegetable Crop Residues for Reuse in Cultivation. Journal of Environmental Science and Health, Part B 39: 169–183.
Mengqi, Z., Shi, A., Ajmal, M., Ye, L., Awais, M., 2023. Comprehensive review on agricultural waste utilization and high-temperature fermentation and composting. Biomass Conversion and Biorefinery 13: 5445–5468.
Nkwachukwu, O., Chima, C., Ikenna, A., Albert, L., 2013. Focus on potential environmental issues on plastic world towards a sustainable plastic recycling in developing countries. International Journal of Industrial Chemistry 4: 34.
Pane, C., Celano, G., Piccolo, A., Villecco, D., Spaccini, R., Palese, A. M., Zaccardelli, M., 2015. Effects of on-farm composted tomato residues on soil biological activity and yields in a tomato cropping system. Chemical and Biological Technologies in Agriculture 2: 4.
Porichha, G. K., Hu, Y., Rao, K. T. V., Xu, C. C., 2021. Crop residue management in india: Stubble burning vs. other utilizations including bioenergy. Energies 14: 4281.
Ren JiQin, R. J., Yu PeiXian, Y. P., Xu XiaoHong, X. X., 2019. Straw utilization in China-status and recommendations.
Rezig, F. A. M., Mubarak, A. R., Ehadi, E. A., 2013. Impact of organic residues and mineral fertilizer application on soil–crop system: II soil attributes. Archives of Agronomy and Soil Science 59: 1245–1261.
Sarkar, N., Ghosh, S. K., Bannerjee, S., Aikat, K., 2012. Bioethanol production from agricultural wastes: An overview. Renewable Energy 37: 19–27.
Schomberg, H. H., Ford, P. B., Hargrove, W. L., 1994. Influence of crop residues on nutrient cycling and soil chemical properties.
Sharma, R. K., Arora, D. S., 2011. Solid state degradation of paddy straw by Phlebia floridensis in the presence of different supplements for improving its nutritive status. International Biodeterioration & Biodegradation 65: 990–996.
Shinde, R., Shahi, D. K., Mahapatra, P., Singh, C. S., Naik, S. K., Thombare, N., Singh, A. K., 2022. Management of crop residues with special reference to the on-farm utilization methods: A review. Industrial Crops and Products 181: 114772.
Singh, S.P. and Sharma, B.L., 2020. Role of crop residues in improving soil fertility and succeeding crops. Journal of Pharmacognosy and Phytochemistry 9: 258-264.
Sun, R. C., & Sun, X. F. (2002). Fractional and structural characterization of hemicelluloses isolated by alkali and alkaline peroxide from barley straw. Carbohydrate Polymers, 49(4), 415–423.
Sun, R., Fang, J. M., Rowlands, P., Bolton, J., 1998. Physicochemical and Thermal Characterization of Wheat Straw Hemicelluloses and Cellulose. Journal of Agricultural and Food Chemistry 46: 2804–2809.
Tejada, M., Gonzalez, J. L., 2006. Crushed Cotton Gin Compost Effects on Soil Biological Properties, Nutrient Leaching Losses, and Maize Yield. Agronomy Journal 98: 749–759.
Tejada, M., Hernandez, M. T., Garcia, C., 2009. Soil restoration using composted plant residues: Effects on soil properties. Soil and Tillage Research 102: 109–117.
Wang, X., Yang, Z., Liu, X., Huang, G., Xiao, W., Han, L., 2020. The composition characteristics of different crop straw types and their multivariate analysis and comparison. Waste Management 110: 87–97.
Xu Ping, X. P., Sun CaiXia, S. C., Ye XueZhu, Y. X., Xiao WenDan, X. W., Zhang Qi, Z. Q., Wang Qiang, W. Q., 2016. The effect of biochar and crop straws on heavy metal bioavailability and plant accumulation in Cd and Pb polluted soil. Ecotoxicology and environmental safety 132: 94-100.
Yadav, D., Vishwakarma, A. K., Sharma, N. K., Biswas, A. K., Ojasvi, P. R., Kumar, D., Kumawat, A., Singh, D., 2021. Sustaining the properties of black soil in Central India through crop residue management in a conservation-agriculture-based soybean–wheat system. Land Degradation Development 32: 2906–2921.
Zhang, C., Lin, Z., Que, Y., Fallah, N., Tayyab, M., Li, S., Luo, J., Zhang, Z., Abubakar, A. Y., Zhang, H., 2021. Straw retention efficiently improves fungal communities and functions in the fallow ecosystem. BMC Microbiology 21: 52
Zhao, X., Yuan, G., Wang, H., Lu, D., Chen, X., Zhou, J., 2019. Effects of full straw incorporation on soil fertility and crop yield in rice-wheat rotation for silty clay loamy cropland. Agronomy 9: 133.
Zheng, Y., Han, X., Li, Y., Yang, J., Li, N., An, N., 2019. Effects of biochar and straw application on the physicochemical and biological properties of paddy soils in Northeast China. Scientific Reports 9: 16531.
Zheng, Y., Zhao, J., Xu, F., Li, Y., 2014. Pretreatment of lignocellulosic biomass for enhanced biogas production. Progress in Energy and Combustion Science 42: 35–53.

A review on soil quality and ecosystem services: The role of earthworms as bioindicators

Shugyla BAKYTBEK *, Agnieszka JOZEFOWSKA
University of Agriculture in Krakow, Department of Soil Science and Soil Protection; Kraków, Poland

***Corresponding Author**

Shugyla BAKYTBEK
bakytbek.shugyla@gmail.com

Abstract
Earthworms play a vital role in maintaining soil quality and enhancing ecosystem services. Acting as bioindicators and ecosystem engineers, they influence soil structure, nutrient cycling, water regulation, and plant productivity. Their ability to bioaccumulate contaminants, such as heavy metals and pesticides, makes them effective tools for assessing soil health and pollution. Laboratory and field studies demonstrate the utility of earthworm-based methods, including behavioral assays and biomarker analyses, in providing reliable and scalable soil quality evaluations. This review explores earthworms' contributions to ecosystem services as defined by the Millennium Ecosystem Assessment, including provisioning, regulating, supporting, and cultural services. Mechanistic insights into their ecological roles are provided, emphasizing their utility in sustainable agriculture and soil restoration. Despite their recognized importance, gaps remain in standardizing bioindication methods and integrating earthworm data with other soil health indicators. Addressing these challenges can enhance the effectiveness of earthworm-based monitoring systems and promote sustainable ecosystem management.

Keywords: Bioindicators, Earthworms, Ecosystem services, Soil quality

Introduction

Ecosystem services refer to the benefits of ecosystems offer to humans and other species (Millennium Ecosystem Assessment, 2005). There is a close association between biodiversity and these services, as numerous ecosystem services are supported by living organisms (Jax et al., 2005). There is now widespread consensus on the categorization of ecosystem services. The Millennium Ecosystem Assessment (2005) classified these services into four main categories: (i) provisioning services, which include resources like food for humans, freshwater, wood, fiber, and fuel; (ii) regulating services, encompassing functions such as gas and water regulation, climate moderation, flood and erosion control, and biological processes like pollination and disease management; (iii) cultural services, which provide aesthetic, spiritual, educational, and recreational benefits; and (iv) supporting services, which involve nutrient cycling, primary production, habitat provision, and biodiversity maintenance.

Soil quality is recognized as one of the three pillars of environmental quality, alongside water and air quality (Andrews et al., 2002). While water and air quality are primarily defined by pollution levels that directly impact human and animal health or affect natural ecosystems (Carter et al., 1997; Davidson et al., 2000), soil quality encompasses a broader scope. It is often defined as "the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran & Parkin et al., 1994; Doran & Parkinet al., 1996).

Bioindication is essential for assessing soil quality, with earthworms often used as bioindicators due to their ecological importance, abundance, and ease of study (Buckerfield et al., 1997; Paoletti et al., 1999). Earthworm presence and activity typically correlate with improved soil quality. Markert et al. (2003) defined bioindication as a qualitative signal of environmental conditions, while biomonitoring involves measurable bioindication to track trends. Earthworms indicate soil quality via (1) their abundance and diversity, (2) behavioral responses to soil, (3) bioaccumulation of soil chemicals, and (4) stress biomarkers. Earthworms drive key "supporting services" like soil formation (Darwin et al., 1881) and nutrient cycling (Edwards et al., 2004), forming the basis for other ecosystem services (Millennium Ecosystem Assessment, 2005).

Soil Quality and Ecosystem Services

Soils in natural and managed ecosystems act as dynamic, three-dimensional regulators essential for diverse soil functions (Blum et al., 2005; CEC, 2006), which underpin ecosystem services (Hannam & Boer et al., 2004). As one of Earth's most complex biomaterials (Young & Crawford et al., 2004), soil operates at the nexus of the lithosphere, biosphere, hydrosphere, and atmosphere (Szabolcs et al., 1994). Despite its significance, research often prioritizes ecosystem services—provisioning, supporting, regulating, and cultural—over soil itself (Costanza et al., 1997; de Groot et al., 2002; MEA, 2005). While soil formation and distribution are well-studied, understanding of soil functions and services remains limited (Daily et al., 1997; Swinton et al., 2006). Hewitt et al. (2015) highlighted soil's neglect in ecosystem service research and policymaking. Daily et al. (1997) stressed soil's role in economic stability, urging its integration into ecosystem frameworks and policy. Table 1 shows Ecosystem services in 3 different categories.

Table 1. Ecosystem services as categorized by the Millennium Ecosystem Assessment (MEA, 2005), the Economics and Ecosystems and Biodiversity (TEEB, 2010), and the Common International Classification Services (CICES, 2011).

Category	MEA categories	TEEB categories	CICES categories
Provisioning services	Food, fodder, fresh water, fiber, timber, biochemical, genetic and ornamental resources	Food, water, raw materials, medicinal resources, genetic resources, ornamental resources	Biomass, water, meterials, genetic resources, mechanical energy
Regulating services	Air quality and gas regulation, water purification, water regulation, erosion, climate, pollination, pest and disease, primary production, nutrient cycling	Air quality, waste treatment, regulation of water flow, erosion, prevention, climate, biological control	Mediation of gas, waste treatment, water flow, extreme events, atmosphere regulation, soil formation
Cultural services	Spiritual and religious values, esthetic, cultural diversity, recreation, knowledge systems	Spiritual experience, esthetic, inspiration, cultural diversity, knowledge	Spiritual, intellectual, recreation, cognitive development, cultural outputs

Long-term studies of soil formation processes are limited, but understanding the role of earthworms in soil formation is crucial, as it has significant implications for restoring degraded environments such as abandoned quarries, burned areas, or heavily polluted sites. Additionally, bioturbation through which organisms influence soil structure alongside soil formation, may have profoundly impacted evolutionary processes, especially following the emergence of metazoans over 500 million years ago. Therefore, investigating the contributions of earthworms to soil formation could enhance our understanding of both marine and terrestrial ecosystem evolution and functioning (Dietrich & Perron et al., 2006; Kennedy et al., 2006; Meysman et al., 2006).

Earthworms as Bioindicators of Soil Quality

Earthworms, classified within the Oligochaeta class of the phylum Annelida, are terrestrial invertebrates that play vital roles in agro-ecosystems. Typically inhabiting moist soils, these organisms possess soft, cylindrical bodies with bilateral symmetry and metameric segmentation. Their bodies are enveloped by a fine cuticle lacking chitin. In soil ecosystems, earthworms function as natural aerators, grinders, and crushers, facilitating the breakdown of organic material and enhancing chemical and biological processes (Edwards & Bohlen et al., 1996). Earthworms are classified into three primary ecological groups, each influencing soil structure and microbial communities in distinct ways (Thakuria et al., 2010). These categories: anecic, endogeic, and epigeic vary in their effects on soil biological processes (Brown et al., 2000). Anecic earthworms create permanent, vertical burrows that penetrate deep into the soil's mineral layers. They feed on surface organic matter, which they transport into their burrows to undergo microbial pre-decomposition, depositing their casts at the burrow entrance (Bouche et al., 1977; Lavelle et al., 1981; Lee et al., 1985). In contrast, endogeic earthworms inhabit the upper mineral layer, where they construct horizontal tunnels and primarily consume mineral soil, modifying physical soil structures and thereby influencing resource accessibility for other organisms (Jones et al., 1994). Epigeic earthworms live at the soil surface without forming permanent burrows, feeding on litter and humus composed of decaying organic material (McLean & Parkinson, 1998).

Mechanisms by Which Earthworms Enhance Ecosystem Services

Earthworms contribute significantly to ecosystem services by improving soil health, structure, and fertility through a variety of mechanisms. Here's an overview of the main ways earthworms enhance ecosystem services:

Soil structure: Earthworms regulate soil structure by creating pores and breaking down macroaggregates formed by compacting species. This dynamic interaction between compacting and de-compacting earthworms contributes to soil stability and functionality (Oades et al., 1993; Milleret et al., 2009a,b; Blanchart et al., 1997).

Water regulation: Earthworms enhance soil porosity and water regulation through their burrowing and casting activities, which facilitate water infiltration and retention. These effects can reduce erosion by up to 50% and improve water dynamics, particularly in tropical regions (Pérès et al., 1998; Sharpley et al., 1979; Shuster et al., 2002).

Nutrient cycling: By breaking down organic matter, earthworms increase its accessibility and release essential nutrients, especially nitrogen. Their activities also promote nitrogen mineralization and interact with other soil organisms, enhancing nutrient cycling efficiency (Ingham et al., 1985; Lee et al., 1985; Bityutskii et al., 2002; Butenschoen et al., 2009).

Plant growth and productivity: Earthworms generally boost above-ground plant biomass and influence nitrogen composition, though effects on root growth vary. Their impact depends on earthworm density, plant type, and environmental factors, highlighting their role in shaping biodiversity and productivity (Brown et al., 1999; Scheu et al., 2003; Chan et al., 2004; Quaggiotti et al., 2004; Eisenhauer & Scheu, 2008).

2.1.5. Pollution remediation: Earthworms aid in pollution remediation by increasing metal bioavailability and plant uptake in contaminated soils. While their activity typically elevates metal concentrations in plant tissues, variability across species, soil conditions, and contaminants poses challenges for quantification (Abdul Rida et al., 1996; Ma et al., 2003, 2006; Wen et al., 2004; Cheng et al., 2005; Liu et al., 2005; Ruiz et al., 2011).

Bioindication with Earthworms in Laboratory Assays

Laboratory assays using earthworms, such as the Avoidance test (ISO 2008; Yeardley et al., 1996; Hund-Rinke & Wiechering, 2001) and Two-Dimensional terraria (Evans et al., 1947; Schrader & Joschko, 1991), effectively assess soil quality and contamination. These methods focus on behavioral responses and ecological interactions, providing reproducible insights into soil health (Fründ et al., 2010; Fründ et al., 2005).

Latest earthworm-based bioindicator techniques

Modern earthworm-based bioindicator techniques provide a multi-faceted approach to assessing soil health and environmental contamination. Table 2 presents several recent studies showcasing techniques that use earthworms as bioindicators in soil quality and pollution assessment. These techniques support sustainable agriculture and help guide soil restoration efforts by offering precise, adaptable tools to measure soil ecosystem health.

Table 2. Recent study techniques using earthworms as bioindicators

Technique	Description	References
Biomarker Analysis	Measures enzyme activity (e.g., AChE, GST) and stress proteins in earthworms to detect soil contamination	Zavala-Cruz et al., 2023
Behavioral Assays	Observes earthworm avoidance, feeding behavior and mvemrnt in contaminated soils	Kanianska et al., 2022
Genetic Markers	Uses DNA/RNA changes in earthworms to reveal exposure to heavy metals and pesticides	Marinussen et al., 2021
Microbial interaction studies	Examines changes in soil microbial communities linked to earthworm activity and health	Zavala-Cruz et al., 2023
Bioaccumulation and Toxicity tests	Assesses heavy metal and pesticide accumulation in earthworm tissues and potential effects on soil fertility	Kim et al., 2023
Earthworm diversity and Biomass Monitoring	Monitors changes in earthworm population and biomass across gradients of pollution	Wang et al., 2023

Conclusion

Earthworms are indispensable to maintaining soil health and ensuring the delivery of vital ecosystem services. Their roles in enhancing soil structure, nutrient cycling, and water regulation make them key players in sustainable agriculture and environmental restoration. Furthermore, earthworms serve as reliable bioindicators, offering critical insights into soil quality and contamination. Despite these benefits, the integration of earthworm-related research into policy frameworks and ecosystem service models remains limited. To harness their full potential, future efforts should prioritize earthworm-based strategies for soil conservation, ecological restoration, and sustainable land management.

References

Assessment, M. E. (2005). Ecosystems and human well-being: wetlands and water. World Resources Institute.

Jax, K. (2005). Function and "functioning" in ecology: what does it mean? Oikos, 111(3), 641-648.

Andrews, S. S., Karlen, D. L., & Mitchell, J. P. (2002). A comparison of soil quality indexing methods for vegetable production systems in Northern California. Agriculture, ecosystems & environment, 90 (1), 25-45.

Carter, D. R., Vogiatzis, M., Moss, C. B., & Arvanitis, L. G. (1997). Ecosystem management or infeasible guidelines? Implications of adjacency restrictions for wild life habitat and timber production. Canadian Journal of Forest Research, 27 (8), 1302-1310.

Doran, J. W., & Parkin, T. B. (1994). Defining and assessing soil quality. Defining soil quality for a sustainable environment, 35, 1-21.

Buckerfield, J. C., Lee, K. E., Davoren, C. W., & Hannay, J. N. (1997). Earthworms as indicators of sustainable production in dryland cropping in southern Australia. Soil Biology and Biochemistry, 29 (3-4), 547-554.

Paoletti, M. G. (1999). Using bioindicators based on biodiversity to assess landscape sustainability. In Invertebrate biodiversity as bioindicators of sustainable landscapes (pp. 1-18). Elsevier.

Markert, B. A., Breure, A. M., & Zechmeister, H. G. (Eds.). (2003). Bioindicators and biomonitors. Elsevier.

Feller, C., Brown, G. G., Blanchart, E., Deleporte, P., & Chernyanskii, S. S. (2003). Charles Darwin, earthworms and the natural sciences: various lessons from past to future. Agriculture, Ecosystems & Environment, 99(1-3), 29-49.

Edwards, A. M., Platt, T., & Sathyendranath, S. (2004). The high-nutrient, low-chlorophyll regime of the ocean: limits on biomass and nitrate before and after iron enrichment. Ecological Modelling, 171 (1-2), 103-125.

Dietrich, W. E., & Perron, J. T. (2006). The search for a topographic signature of life. Nature, 439(7075), 411-418.

Kennedy, A. C., & Stubbs, L. (2006). Soil microbial communities as indicators of soil health. Annals of arid zone, 45 (3 & 4).

Meysman, F. J., Middelburg, J. J., & Heip, C. H. (2006). Bioturbation: a fresh look at Darwin's last idea. Trends in Ecology & Evolution, 21 (12), 688-695.

Aeschlimann, U., Nösberger, J., Edwards, P. J., Schneider, M. K., Richter, M., & Blum, H. (2005). Responses of net ecosystem CO2 exchange in managed grassland to long-term CO2 enrichment, N fertilization and plant species. Plant, Cell & Environment, 28(7), 823-833.

Hannam, I., & Boer, B. (2004). Drafting legislation for sustainable soils: a guide (No. 52). IUCN.

Young, I. M., & Crawford, J. W. (2004). Interactions and self-organization in the soil-microbe complex. Science, 304(5677), 1634-1637.

Szabolcs, I. (1994). The concept of soil resilience.

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., ... & Van Den Belt, M. (1997). The value of the world's ecosystem services and natural capital. nature, 387(6630), 253-260.

De Groot, R. S., Wilson, M. A., & Boumans, R. M. (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological economics, 41 (3), 393-408.

Swinton, S. M., Lupi, F., Robertson, G. P., & Landis, D. A. (2006). Ecosystem services from agriculture: looking beyond the usual suspects. American journal of agricultural economics, 88(5), 1160-1166.

Sukhdev, P., Wittmer, H., & Miller, D. (2014). The economics of ecosystems and biodiversity (TEEB): challenges and responses. Nature in balance: the economics of biodiversity, 135-152.

Haines-Young, R., & Potschin, M. (2012). Common international classification of ecosystem services (CICES, Version 4.1). European Environment Agency, 33, 107.

Binet, F., Fayolle, L., Pussard, M., Crawford, J. J., Traina, S. J., & Tuovinen, O. H. (1998). Significance of earthworms in stimulating soil microbial activity. Biology and fertility of soils, 27, 79-84.

Cunha, L., Brown, G. G., Stanton, D. W., Da Silva, E., Hansel, F. A., Jorge, G., ... & Kille, P. (2016). Soil animals and pedogenesis: the role of earthworms in anthropogenic soils. Soil Science, 181(3/4), 110-125.

Thakuria, D., Schmidt, O., Finan, D., Egan, D., & Doohan, F. M. (2010). Gut wall bacteria of earthworms: a natural selection process. The ISME journal, 4(3), 357-366.

Brown, G. G., Edwards, C. A., & Brussaard, L. (2004). How earthworms affect plant growth: burrowing into the mechanisms. In Earthworm ecology (pp. 13-49). CRC Press.

Bottinelli, N., & Capowiez, Y. (2021). Earthworm ecological categories are not functional groups. Biology and Fertility of Soils, 57(2), 329-331.

Lee, K. E. (1985). Earthworms: their ecology and relationships with soils and land use (pp. 411-pp).
Scheu, S., Schlitt, N., Tiunov, A. V., Newington, J. E., & Jones, H. T. (2002). Effects of the presence and community composition of earthworms on microbial community functioning. Oecologia, 133, 254-260.
McLean, M. A., & Parkinson, D. (1998). Impacts of the epigeic earthworm Dendrobaena octaedra on microfungal community structure in pine forest floor: a mesocosm study. Applied Soil Ecology, 8(1-3), 61-75.
Oades, J. M. (1993). The role of biology in the formation, stabilization and degradation of soil structure. In Soil structure/soil biota interrelationships (pp. 377-400). Elsevier.
Milleret, R., Le Bayon, R. C., Lamy, F., Gobat, J. M., & Boivin, P. (2009). Impact of roots, mycorrhizas and earthworms on soil physical properties as assessed by shrinkage analysis. Journal of Hydrology, 373 (3-4), 499-507.
Bityutskiĭ, N. P., Lapshina, I. N., Lukina, E. I., Solov'eva, A. N., Patsevich, V. G., & Vygovskaya, A. A. (2002). Role of earthworms in mineralization of organic nitrogen compounds in the soil.
Rida, A. M. M. A., & Bouché, M. B. (1997). Heavy metal linkages with mineral, organic and living soil compartments. Soil Biology and Biochemistry, 29(3-4), 649-655.
Fründ, H. C., Graefe, U., & Tischer, S. (2010). Earthworms as bioindicators of soil quality. In Biology of earthworms (pp. 261-278). Berlin, Heidelberg: Springer Berlin Heidelberg.
Schrader, S. (1993). Semi-automatic image analysis of earthworm activity in 2D soil sections. In Soil Structure/Soil Biota Interrelationships (pp. 257-264). Elsevier.
Zavala-Cruz, J., et al. (2023). Biomarker analysis for enzyme activity and stress protein measurement in earthworms to detect soil contamination. International Journal of Ecology.
Kanianska, A., et al. (2022). Behavioral assays for observing earthworm avoidance, feeding behavior, and movement in contaminated soils. Sustainability.
Marinussen, M., et al. (2021). Genetic markers using DNA/RNA changes in earthworms to reveal exposure to heavy metals and pesticides. Environmental Pollution Journal.
Zavala-Cruz, J., et al. (2023). Microbial interaction studies on soil microbial communities linked to earthworm activity and health. Journal of Soil Health.
Kim, H., et al. (2023). Bioaccumulation and toxicity tests for assessing heavy metal and pesticide accumulation in earthworm tissues and potential effects on soil fertility. Environmental Science.
Wang, X., et al. (2023). Earthworm diversity and biomass monitoring across gradients of pollution. Agricultural Science.

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

Predicting and mapping of soil erodibility factor using artificial neural network and geospatial approach: A case study of Samsun, Türkiye

Wudu ABIYE [1,2*], Orhan DENGIZ [1] and Sena PACCI [1]
[1]Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye
[2]University of Agriculture in Krakow. Department of Soil Science and Soil Protection; Kraków, Poland

***Corresponding Author**

Wudu ABİYE
wuduabiye@gmail.com

Abstract

Soil erosion is a significant environmental issue that threatens the soil's sustainability and fertility, with soil erodibility being a critical factor in determining erosion rates. Based on its physical and chemical characteristics, soil erodibility indicates the soil's susceptibility to erosion. The objectives of this study were to estimate and map soil erodibility throughout the study area by utilizing the K-factor from the Wischmeier equation, evaluate additional soil erodibility indicators, including the structural stability index, clay ratio, crust formation, and dispersion ratio, and create a predictive model for soil erosion risk using artificial neural networks (ANN) and geospatial technologies. High-resolution spatial maps of soil erosion risk were generated to inform land management and conservation strategies. The soil erodibility and associated indicators, including the dispersion ratio, crust formation, and clay ratio, were predicted using an ANN model that was developed in MATLAB R2024a. Furthermore, Orginpro 2021b was applied to investigate the correlations between soil properties through statistical analyses, such as principal component analysis (PCA) and correlation assessment. ArcGIS 10.7.1 was employed to generate spatial maps of predicted and observed soil erodibility. Results showed that the observed soil erodibility values ranged from 0.194 to 0.253 t ha hrMJ^{-1}·mm^{-1}, while the predicted values ranged from 0.171 to 0.318 t·ha·hr·MJ^{-1}·mm^{-1}. The ANN model exhibited a high level of predictive accuracy, with an R2-value of 99.42% for soil erodibility prediction. This research emphasizes the efficacy of integrating geospatial technologies and machine learning techniques to precisely predict and map soil erodibility, thereby providing valuable insights for sustainable land management strategies and erosion control.
Keywords: ANN, Geospatial technologies, K-factor, sustainable land management, spatial analysis

Introduction

Soil erosion indeed poses significant challenges to agriculture, water quality, and ecosystems. The factors influencing soil erodibility include soil texture, organic matter content, soil structure, and permeability. These elements determine how easily soil particles can be detached and transported by rainfall and runoff (Sulaeman etal, 2020, Borrelli etal, 2019). Soil erodibility is influenced by various factors, including soil texture, organic matter content, soil structure, and permeability (Borrelli, et al, 2020). Different soils exhibit different rates of erosion under similar conditions due to these inherent properties. For instance, soils with high clay content tend to have lower erodibility compared to sandy soils. Additionally, land use practices, such as agriculture and deforestation, significantly impact soil erodibility by altering soil structure and organic matter content (Larionov et al, 2018).

Recent studies have highlighted the role of soil organic carbon in reducing soil erodibility. Higher organic carbon content improves soil structure and increases resistance to erosion (Jiachen etal, 2022). Furthermore, advancements in remote sensing and geospatial technologies have enabled more precise mapping of soil properties, enhancing our understanding of spatial variability in soil erodibility (Singh et al, 2022). Mapping the spatial distribution of soil erodibility values is crucial for identifying areas that are most susceptible to erosion (Thenkabail,2024). This information can guide the implementation of targeted soil conservation measures and land management practices. Integrating geospatial technology with machine learning, particularly Artificial Neural Networks (ANN), enhances the accuracy and efficiency of soil erodibility mapping. ANNs can model complex relationships between soil properties and erodibility, providing more reliable predictions (Yaghoubi, etal, 2024).

This study aims to provide a comprehensive understanding of the factors affecting soil erodibility and their spatial variability. By integrating geospatial technology with machine learning, we can develop more precise and effective soil conservation strategies. We hypothesized that soil erodibility values vary depending on soil type and other factors, and mapping these variations will help prioritize areas susceptible to soil erosion.

Material and Methods

Study area, Sample and Dataset

The study area is a micro-watershed located along the southern shore of the Black Sea in Samsun, Turkiye, encompassing an area of 1337 hectares. Geographically, it spans from 41° 23' 35.13" North latitude to 41° 23' 35.13" East longitude (Figure 1), with elevations varying from 59 to 532 meters above sea level (Figure 2). The topography of this region displays a varied spectrum of inclines, ranging from 0% to 74% (Figure 2). The average annual precipitation is approximately 735 mm, resulting in relatively humid circumstances, but the average annual temperature is about 14°C. Seasonal temperature extremes fluctuate between around 6°C and 22°C. The major land use types of the study areas are agricultural, artificial, forest, pasture and water bodies (Figure 2).

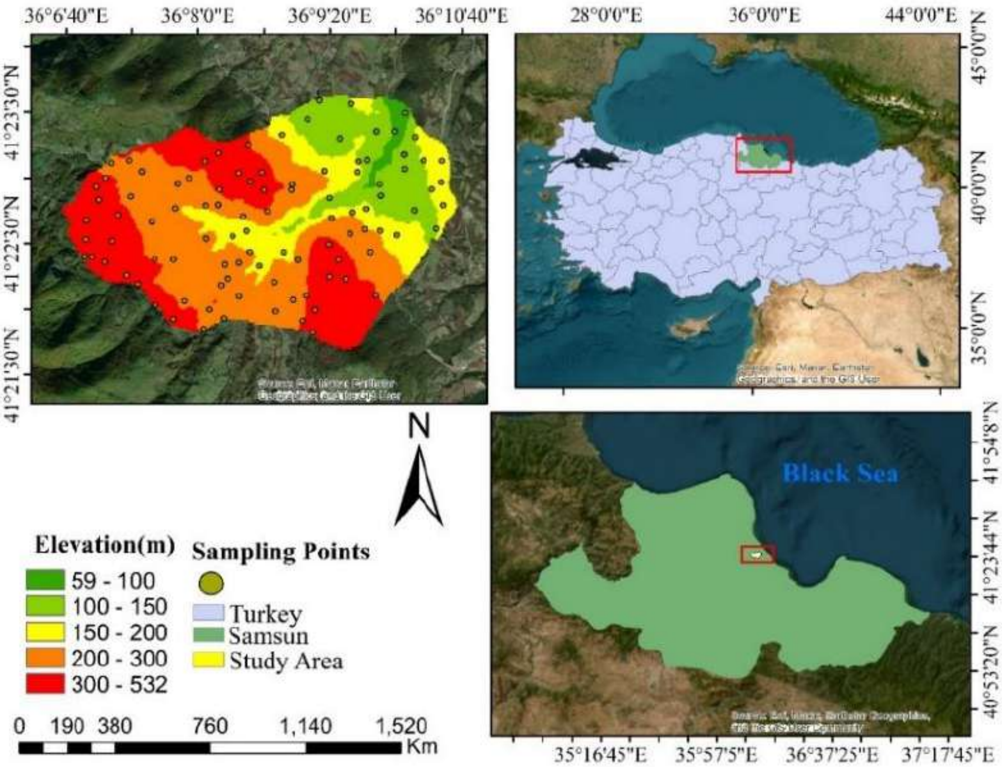


Figure 1. Location map of the Study Area

For this study, ninety-nine soil samples were collected from different land use types within the watershed cultivated land, forest land, and pasture land identified and distributed using Google Earth. All analyses in this study were conducted using standard methodologies appropriate for each soil properties. Soil texture was determined using the hydrometer method (Bouyoucos, 1951). Organic matter content was measured using the Walkley-Black method Kacar (2009). In the micro-watershed, soil samples were collected from 99 designated sampling points to analyze various physical and chemical properties, including sand, silt, clay and very fine sand fractions, dispersion ratio, and organic carbon content. These properties were assessed to determine soil erodibility using the Wischmer Soil erodibility equation (Equation 1).

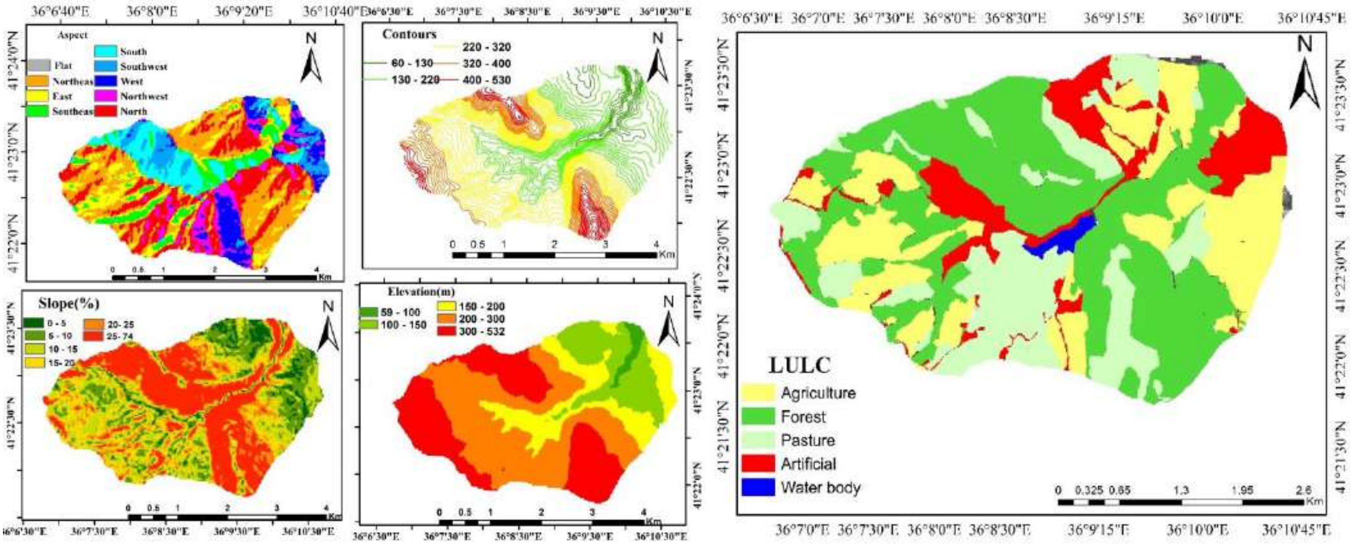


Figure 2. Aspect(A), Hill Contours (B), Elevation (C) and Slope (D)and LULC maps of the study area

Eight soil properties were utilized as input variables to predict soil erodibility using an artificial neural network (ANN) model. A hiding layer with 10 neurons and an output layer that represented the soil erodibility factor comprised the network framework. Optimizing predictive performance, the ANN implemented the Levenberg-Marquardt (LM) algorithm and implemented the feed-forward backpropagation technique.

Determination of Soil erodibility

$$K = \frac{(2.1X10^{-4})(12-OM)M^{1.14}+3.25(S-2)+2.5(P-3)}{100}$$ (Eq1) Wischmer (1969)

OM = Organic matter content (%) of the top 20 cm of soil

$$M = \frac{(\%\text{silt}+\%\text{very fine sand})(100-\text{clay}\%)}{100}$$ (Eq2)

The texture factor that depends on silt, very fine sand and clay content

S = Soil structure code, with values based on soil aggregation (1 = very fine granular, 2 = fine granular, 3 = medium or coarse granular, 4 = blocky, platy, or massive) p= Permeability class of the soil (ranges from 1 = rapid to 6 = very slow)

Artificial Neural Network (ANN)

Machine learning (ML) is a significant technique in research, facilitating the creation of prediction models capable of analyzing extensive datasets with minimal human involvement. The Artificial Neural Network (ANN) is an incredibly successful method in machine learning, designed to model the structure and function of the human brain (Valenzuela et al, 2023). Artificial Neural Networks comprise interconnected layers of nodes or "neurons" that analyze input data, determine patterns, and make predictions (Abraham,2005).

Results And Discussion

Soil and erodibility properties

The mean values of the analyzed soil properties provide important insights into soil characteristics and their potential implications for agricultural productivity and management. The organic matter content is 5.1%, which is moderate and contributes to soil fertility, water retention, and microbial activity, aligning with the findings of Lal (2006). The substantial clay content (41.2%) indicates considerable water retention and nutrient-holding capacity; however, it may also result in compaction and decreased permeability, as observed by Brady and Weil (2002). The contents of silt (23.6%) and sand (35.4%) create a balanced texture that enhances fertility and drainage, consistent with the findings of Horn et al. (1994). Fine sand (26.2%) facilitates capillary water movement, as noted by Gee and Or (2002). A permeability of 4.8% suggests moderate water movement through the soil, highlighting the impact of clay on hydraulic conductivity (Gupta & Larson, 1979). The Structural Stability Index (SSI, 12.9%) indicates moderate resistance to degradation, in line with Dexter's (2004) statements that SSI values exceeding 10% maintain structural integrity (Table 1). The dispersion ratio of 22.8% indicates moderate stability against erosion, whereas the crust formation of 8.7% suggests potential risks to infiltration and seed germination, as observed by Valentin and Bresson (1992). Although the soil exhibits favourable fertility and stability, it is essential to implement management practices, including organic amendments and erosion control, to mitigate potential risks related to compaction, erosion, and surface sealing.

Table 1: Descriptive Statistical value of soil properties

Soil Properties	Mean	S. D	Min	Max	Range	CV	Skew	Kurt
OM%	5.1	2.0	0.1	9.6	9.4	0.3	0.2	0.3
Clay%	41.2	16.0	3.2	64.0	60.8	0.4	-0.4	-0.9
Silt%	23.6	5.36	7.49	39.5	5.75	0.23	0.03	1.42
Sand%	35.4	18.2	5.8	86.3	80.6	0.5	0.5	-0.45
VFS%	26.2	17.1	3.5	80.9	77.3	0.7	0.7	0.0
Perm %	4.8	1.4	2.0	6.0	4.0	0.3	-0.8	-0.6
Str	3	1	1	4	3	0	-1	-1
CR%	2.3	3.6	0.6	30.7	30.2	1.5	6.0	43.5
MCR%	1.7	1.6	0.5	10.0	9.5	0.9	2.8	9.6
CLOM%	8.7	4.9	0.4	35.2	34.8	0.6	1.7	7.4
SSI%	12.9	9.0	0.7	67.3	66.6	0.7	2.9	14.1
DR%	22.8	8.5	10.0	48.9	38.8	37.4	1.2	1.4
CF%	8.7	4.9	0.4	35.2	34.8	0.6	1.7	7.4
OK	0.1	0.0	0.0	0.2	0.2	55.5	0.2	-0.3
PK	0.23	0.06	0.12	0.39	0.27	0.24	0.82	038

OM: organic matter, VFS: Veryfine Sand, CR: clay ratio, MCR: CLOM: critical level of organic matter, SSI: Soil structure index, DR: dispersion ratio, Kurt: Kurtosis, Skew; Skewness, Ok: Observed soil erodibility, PK: Predicted soil erodablity, Perm: permeability and Str: structure code

Pearson Correlation of Soil Properties

The correlation graph shows strong links between soil characteristics and erodibility (K). Sand and clay have opposite impacted on soil texture, with increased clay concentration reducing sand proportions (-0.96). Sand's very negative correlation with permeability (-0.88) indicates its role in improving drainage and lowering water retention, while clay's tiny particles impede water movement (0.91). OM is favorably associated with the critical level of organic matter (CLOM, 0.74), highlighting its role in soil structure and stability. The structure stability index (SSI) is marginally linked with CLOM (0.78) and crust formation (CF, 0.85), indicating that organic matter reduces soil crusting and improves structural integrity. Very fine sand (VFS) correlates highly with sand (0.88), affecting soil texture and water infiltration (Figure 3). The soil erodibility factor (K) correlates less with most parameters, suggesting clay, organic content, and structural stability affect it. Brady and Weil (2002) and Lal (2006) agree that texture and organic matter affect water transport and soil resilience and that organic additions reduce soil erosion. Clay, organic matter, and fine sand management affect soil health and erodibility.

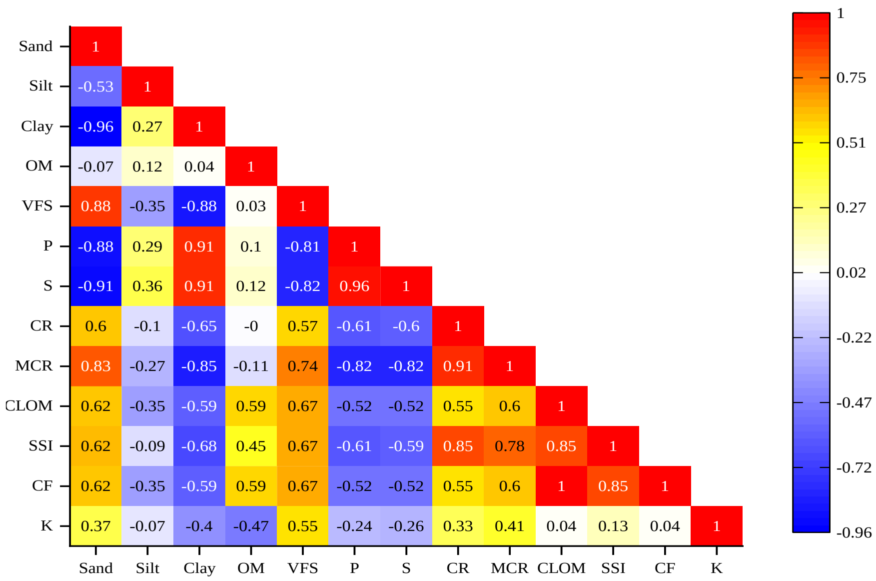


Figure 3. Correlation between soil properties

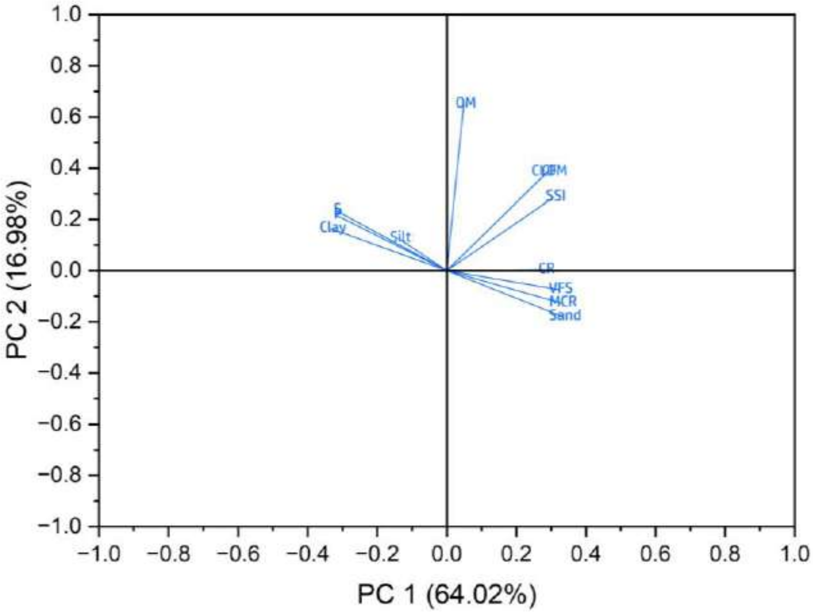


Figure 4. Principal component analysis of the soil properties

Principal Component Analysis -Biplot

The Principal Component Analysis (PCA) plot shows the property of soil relationships, with PC1 explaining 64.02% and PC2 16.98% of the variance. Sand, VFS, MCR, and crust formation positively affect PC1, which accounts for most of the variance. These variables coincide with effectively suggesting they dominate texture-related features and soil erodibility. Clay and silt are adversely related to PC1, showing their opposite impact on soil stability and connection with sandy components. Positively loaded organic matter (OM), critical level of organic matter (CLOM), and structural stability index (SSI) form PC2, which captures 16.98% of the variance (Figure 4). This shows that organic matter strongly improves soil structure and reduces erosion. The clay ratio (CR) is closer to sandy components but still distinct, indicating its intermediate function in soil texture and related processes. The biplot shows these relationships. Sand, VFS, MCR, and CF cluster together to emphasize their interdependence, while OM, CLOM, and SSI cluster indicate their impact on soil structural stability. Clay's orthogonal alignment with sand and associated variables emphasizes their low overlap. These results demonstrate the importance of texture (sand and MCR) and structure (OM and CLOM) in soil erodibility and crust formation.

Spatial distribution and ANN process of soil erodibility factors

Various interpolation techniques, aligned with appropriate models, have been employed to map the spatial distribution of soil erodibility. These techniques utilize observed and predicted values, evaluated based on the root mean square error, to delineate the influencing factors. The results indicate that the kriging geostatistical method with a simple kriging method in spherical method performed better than the other methods, as reflected by the lower root mean square error (RMSE) values. The Kriging-Simple method, used for the observed data, resulted in an RMSE of 0.0531, demonstrating that it provided a reliable interpolation for the observed dataset. This low RMSE suggests that Kriging was effective in modelling the spatial distribution of the observed values, although it may not fully capture more complex spatial patterns. Similarly, the Kriging-simple method, applied to the predicted data, produced a slightly lower RMSE of 0.0535, indicating better accuracy in capturing the spatial variability of the predicted data. The ability of kriging -simple to generate a smoother and more continuous surface, coupled with its lower error, suggests that it is more suited for datasets with complex spatial structures. Overall, both methods performed well, but the kriging with the simple method was more accurate in predicting spatial patterns, as evidenced by the lower RMSE.

The R values for predicting soil erodibility-K and its associated factors are significantly high across all datasets, indicating robust model performance. The training sample R of 0.99 indicates an optimal fit with the training data, suggesting that the model has successfully captured the variance in soil erodibility factors within this subset. The R^2 values of 99% (0.99) for both validation and testing datasets indicate the model's strong generalization capabilities, preserving a high level of predictive accuracy on unseen data. The R-value of 0.99 supports these findings, indicating that the model consistently predicts soil erodibility across different data sets (Figure 5). The high degree of consistency underscores the model's efficacy in representing the relationships between soil erodibility and its influencing factors. The slight decrease from training to validation/testing data is a common phenomenon that highlights the inherent variability present in real-world applications.

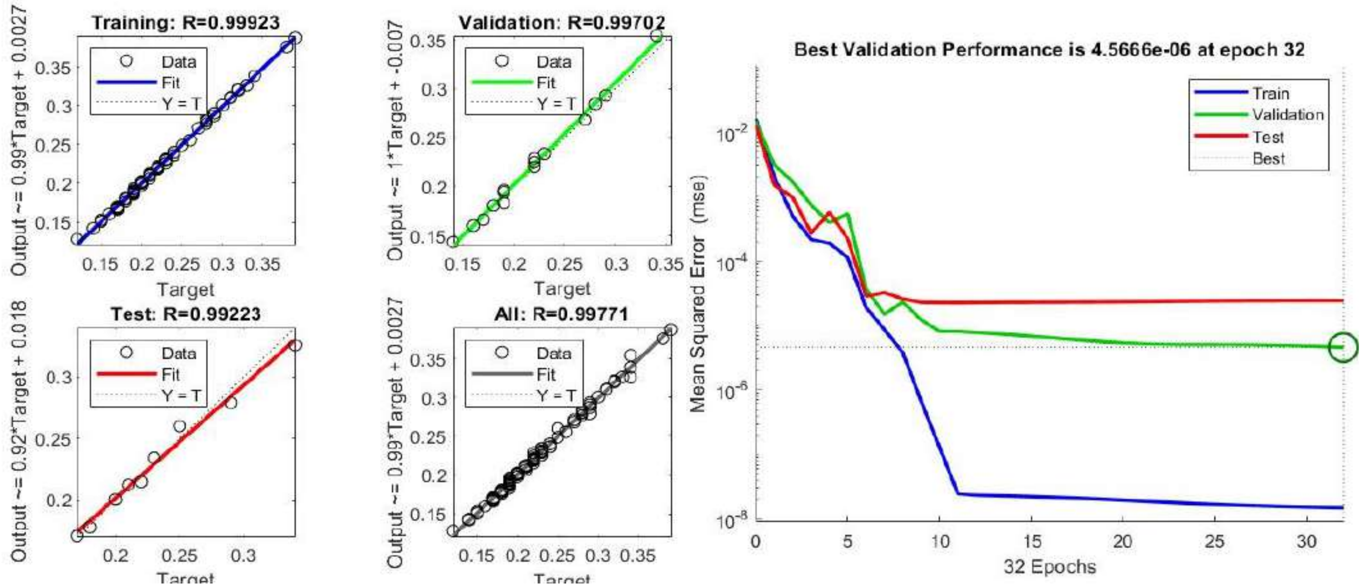


Figure 5. Results of Regression between Output Data and Targets for the Levenberg-Marquardt and Levenberg-Marquardt combination performance graph of soil erodibility -K factor

At epoch 32, the model predicted soil erodibility accurately based on texture and organic content with the lowest RMSE. The model's best performance was reached when the Levenberg-Marquardt algorithm captured non-linear interactions and training did not improve it (Figure 5). This shows the model generalizes effectively and that prolonged training may cause overfitting, underlining the significance of ending at the ideal epoch for accurate environmental predictions.

Soil erodibility-K factor

Based on the analysis, soil erodibility measurements ranging from 0.194 to 0.253 t·ha·hr·MJ^{-1}·mm^{-1} indicate moderate to low erosion risk in the region. The predicted values of 0.171 to 0.318 t·ha·hr·MJ^{-1}·mm^{-1} (Figure 8) indicate a wider range of erodibility, with some areas expected to face higher erosion risks due to factors beyond the observed data, such as land use changes or climate variability. The model's wider predicted range demonstrates that while some areas may have lower predicted erodibility, others may be more vulnerable, emphasizing the need for targeted soil conservation strategies, especially in regions with higher predicted values. The difference between observed and projected values emphasizes model validation and possible improvements for more accurate future forecasts.

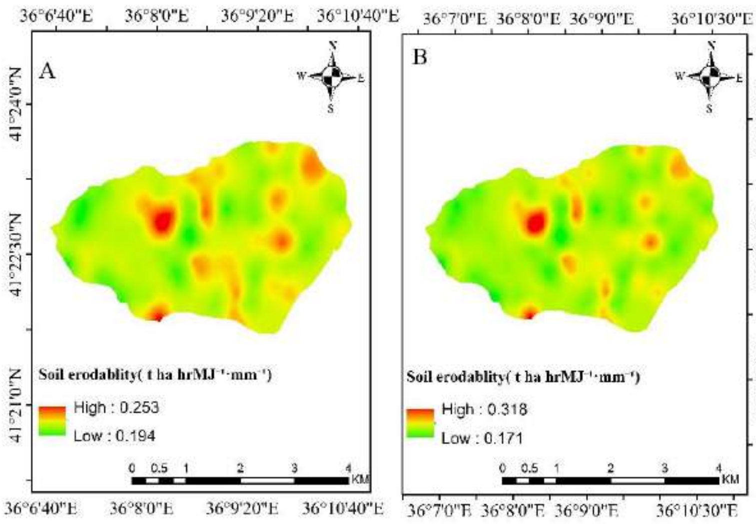


Figure:8 Soil erodibility-K maps (A): Observed and (B); Predicted

Conclusion

The primary objective of this study was to test the predictive power of artificial neural networks (ANNs) about soil erosion sensitivity and its indicators in a micro-catchment by applying the Wischmer equation. The values of soil erodibility, also known as the K-factor, differ between 0.171 and 0.318 $t\cdot ha\cdot hr\cdot MJ^{-1}mm^{-1}$. Organic matter (OM), soil texture (sand, silt, and clay), soil permeability, and soil structure codes were the main soil variables that affected the erodibility factor. From these factors, other indications of soil erodibility were generated, including the dispersion ratio, clay ratio, aggregate stability of the soil, soil structure index, modified clay ratio, and critical levels of organic matter. The geostatistical interpolation method, employing simple kriging and the spherical model, exhibited strong performance with a low root mean square error of 0.0531. Predicting soil erodibility and associated soil quality indicators using ANN proved to be a highly accurate method. Soil erodibility has a correlation coefficient of 0.99 between the two sets of data. According to these findings, soil erodibility can be accurately predicted using ANN and direct soil analysis, without taking pedogenic and environmental factors into serious consideration. On the other hand, the study's smaller sample size and focused focus on a single micro-catchment might lead to inaccurate ANN predictions. To ensure that ANN models can accurately forecast soil erodibility across a variety of areas and land use patterns, future studies should broaden the dataset. This method has the potential to make ANN more accurate in predicting soil parameters in a variety of environments.

Acknowledgments

This research was supported by Ondokuz Mayıs University under the project code BAP01-2024-5185. The authors thank all contributors for their valuable support.

References

Abraham, A. (2005). Artificial neural networks. Handbook of measuring system design.

Alewell C, Borrelli P, Meusburger K, Panagos P (2019) Using the USLE: chances, challenges and limitations of soil erosion modelling. Int Soil Water Conserv Res 7(3):203–225.

Borrelli, P., Robinson, D. A., Panagos, P., Lugato, E., Yang, J. E., Alewell, C., ... & Ballabio, C. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). Proceedings of the National Academy of Sciences, 117(36), 21994-22001.

Borrelli, P., Robinson, D. A., Panagos, P., Lugato, E., Yang, J. E., Alewell, C., ... & Ballabio, C. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). Proceedings of the National Academy of Sciences, 117(36), 21994-22001.

Larionov, G. A., Bushueva, O. G., Gorobets, A. V., Dobrovolskaya, N. G., Kiryukhina, Z. P., Krasnov, S. F., ... & Sudnitsyn, I. I. (2018). Experimental study of factors affecting soil erodibility. Eurasian soil science, 51, 336-344.

Nikseresht, F., Lenka, L., & Saleh, Y. Assessing the Effects of Climate Change and Land Use/Land Cover on Wind Erosion in Western Slovakia Using GIS and Analytic Hierarchy Process. Land Cover on Wind Erosion in Western Slovakia Using GIS and Analytic Hierarchy Process.

Pan, J., Liu, C., Li, H., Wu, Q., Dong, Z., & Dou, X. (2022). Soil-resistant organic carbon improves soil erosion resistance under agroforestry in the Yellow River Flood Plain, of China. Agroforestry Systems, 96(7), 997-1008.

Singh, V. P., Yadav, S., Yadav, K. K., Perez, G. A. C., Muñoz-Arriola, F., & Yadava, R. N. (Eds.). (2022). Application of Remote Sensing and GIS in Natural Resources and Built Infrastructure Management. Springer.

Sulaeman, D., & Westhoff, T. (2020). The causes and effects of soil erosion, and how to prevent it. World Resources Institute: Washington, DC, USA, 4.

Thenkabail, P. S. (Ed.). (2024). Remote Sensing Handbook, Volume IV.

Valenzuela, O., Catala, A., Anguita, D. et al. New Advances in Artificial Neural Networks and Machine Learning Techniques. Neural Process Lett 55, 5269–5272 (2023). https://doi.org/10.1007/s11063-023-11350-w

Yaghoubi, E., Khamees, A., & Vakili, A. H. (2024). A systematic review and meta-analysis of artificial neural network, machine learning, deep learning, and ensemble learning approaches in the field of geotechnical engineering. Neural Computing and Applications, 1-45.

Exploring yellow mealworm (Tenebrio molitor L.) frass as a soil amendment and biotic stress mitigator in crop production: A brief review

Zain UL ABADIN *, Lyubka KOLEVA-VALKOVA
Department of Plant Physiology, Biochemistry, and Genetics, Agricultural University Plovdiv, Bulgaria

***Corresponding Author**

Zain UL ABADİN
zainulabadin1998@gmail.com

Abstract

Frass from yellow mealworms (*Tenebrio molitor L.*) is a nutrient-dense feedstock which enhances soil fertility through Nitrogen, Phosphorus, and Potassium enrichment. It has complementary properties of plant and natural humus and improves microbial diversity. It also promotes plant tolerance to biotic stressors like pests and diseases by activating defense pathways. Frass application promotes beneficial microbes' activity and soil structure, which are important for long-term soil health and sustainability. Nevertheless, there are some limitations, such as the ease of variability on the nutrient composition depending on the diet and rearing conditions applied to insects and the feasibility of its utilization in economics. Further fieldwork prioritizing the environmental impacts along with the optimal application rates for the frass is worth pursuing through collaboration. Quality certification of frass and research into its comparative advantages to traditional chemical fertilizers will be integral for wider usage. So, this review presents the innovative potential of using *Tenebrio molitor L.* frass in sustainable agriculture, making a case for continued research on optimal deployment strategies and identifying gaps in knowledge.

Keywords: Insect-frass fertilizer, Microbial activity, Nutrient cycling, Organic fertilization, Plant defense, Soil biota

Introduction

The need for sustainable agricultural practices is rapidly growing because of the effects of climate change, population growth, and environmental degradation. These practices take into account environmental, social, and economic goals to provide food while still protecting the ecosystem and community health. Increased consumer awareness behind demand for sustainable goods leads to or pushes transitions into environmentally friendly and socially responsible agriculture. It improves food security through optimal water management while mitigating soil degradation by improving quality and decreasing harmful effects of synthetic fertilizers (Shadeed et al., 2020; Velasco-Muñoz et al., 2018; Nong et al., 2020; Jena et al., 2022).

Considered a byproduct of insects, insect frass (excrement) is one potential beneficial soil amendment that can be applied to crops because of its nutrient value and biochemical activity. Compared to more traditional soil amendments, such as leaf litter, frass is rich in nitrogen and labile carbon (both important for soil fertility), and contains high concentrations of nitrate and ammonium, allowing for rapid plant uptake (Kagata & Ohgushi 2010; Kagata & Ohgushi 2011) However, the fertilizing potential of frass varies from one insect species to another and may involve a careful selection for its use based on crop types and soil specific needs (Beesigamukama et al., 2022). Besides nutrients, frass improves plant resilience; the cricket's frass (*Acheta domesticus L.*) harbors microbes that promote nitrogen fixation, mineral solubilization, and production of growth-promoting compounds, thus enhancing plant resistance to stress conditions including drought (Ferruzca-Campos et al., 2023).

Frass production has been increasing (especially, from black soldier fly: *Hermetia illucens L.*) and promoted as a sustainable fertilizer, with up to 1.5 million tons produced in the EU estimated by the mid-2020s (Gebremikael et al., 2022). Frass, however, especially from mealworm is rich in nitrogen, phosphorus, and potassium, allowing for a quick release of nutrients that are beneficial to crops at critical growth stages and reducing the dependence on synthetic fertilizers (Nyanzira et al. 2023; Nogalska et al., 2024). Frass additionally interacts favorably with soil biota, particularly earthworms that further improve soil health and nutrient features (Dulaurent et al., 2020). This synergy together with reinforced microbial activity enhances nutrient cycling, biotic stress resistance, and the development of sustainable crop systems (Wantulla et al., 2022).

Chemical Composition and Potential Benefits of *Tenebrio molitor L.* Frass

Tenebrio molitor L. (yellow mealworm) frass has been increasingly attracting the attention of researchers as a value-added and organic fertigation product owing to its high nutritional value and bioactive compounds. If mealworms are fed a nutrient-dense diet, it contains indispensable N, P, K in the order of 3.3 %, 2.8 %, and 2.3 %, respectively (Nyanzira et al., 2023). The composition of nutrients is helpful for rapid mineralization, converting nutrients into forms that can be used by plants (Nogalska 2024). Moreover, *Tenebrio molitor L.* frass makes an excellent source of organic carbon, which improves soil structure and aggregation, and water content and aeration that provides a habitat for microorganisms (Houben et al., 2021). In this manner, they significantly contribute to nutrient cycling and consequently improve soil fertility basis of sustainable agriculture. Moreover, soil treatment with mealworm frass induces microbial activity and enhances earthworm populations, providing additional input for soil health (Dulaurent et al., 2020).

In addition to its nutrient content, *Tenebrio molitor L.* frass is also rich in other bioactive compounds that support functions of beneficial microorganisms, which are important to maintain soil health. These communities not only are pathogen suppressive but also help improve nutrient availability (Wantulla et al. 2022). Thus, the combination of consistent nutrient profile together with bioactive properties of frass highlights its capability as a substitute for synthetic fertilizers, which led to over-dependence on agrochemicals and was contrary to sustainable agriculture practices that targeted commodity production with an emphasis on soil fertility and a low ecological footprint (Houben et al., 2021).

Effects of *Tenebrio molitor L.* Frass on Soil Fertility

Studies suggest that frass from mealworms and other insects (including black soldier flies) has the potential as a sustainable alternative to synthetic fertilizers, improving soil physical properties (structure), chemical properties (nutrient retention), or biological properties (microbial activity). In contrast to conventional fertilizers, frass delivers its nutrients over an extended period of time, thus promoting crop nutrition. Houben et al. (2021) suggested that mealworm frass is characterized by relatively efficient mineralization and release of nutrients, which has shown to supply phosphorus (P) and potassium (K) equivalently to mineral fertilizers when applied at 10 t ha^{-1}. Frass releases nutrients in a delayed timeframe, increasing soil fertility and improving soil health through its organic matter content which is beneficial in the long term.

The use of frass also encourages the activity of bacteria and other microorganisms, which is crucial for soil development and nutrient cycling. The organic material in frass serves as an energy source for soil-beneficial microbial communities, enhancing the biological activity that is fundamental for the functioning of healthy soil ecosystems (Gärttling & Schulz, 2021). These changes in microbial dynamics lead to additional aid in stabilizing soil structure and nutrient cycling, which are pillars of sustainable management of soils.

From the environmental point of view, frass has a lot of advantages as well, especially in decreasing the dependence on chemical fertilizer. Frass has the potential to improve soil organic matter and reduce risks of nitrate leaching by immobilizing soil mineral nitrogen (Gärttling & Schulz, 2021). This feature minimizes agricultural runoff, which is one of the major ecological challenges faced by traditional farming. Moreover, due to the presence of organic and inorganic nitrogen in frass, its application reduces ammonia volatilization as it is a major disadvantage associated with synthetic fertilizers, which helps farmers reduce environmental impacts and costs (Gärttling et al., 2020).

Frass seemed promising for the long-term impacts on soil health since it can be improved through amendments; for example, biochar improves its nitrogen retention capacity, stabilizes soil pH, nutrient concentration, and provides healthier soils with more productivity (Beesigamukama et al., 2020). Also, nutrient stability in frass, particularly in soils amended with biochar, indicates opportunities for the long-term sustainable soil benefits that can lead to environmentally sustainable agricultural productivity.

Role of *Tenebrio molitor L.* Frass in Biotic Stress Management

Frass, especially from insects like mealworms and crickets has been evaluated for reducing biotic stress in plants. Frass contributes to increased plant strength through various mechanisms, such as nutrient provision, stimulation of the soil microbial community, and elicitation of plant defense responses. Frass contributes to nutrient-rich soil (nitrogen, phosphorus, and decomposing fungi) which in turn supplies key nutrients needed for defense against biotic stress. According to Houben et al. (2021), mealworm frass has been shown to have a strong impact on the soil, increasing nitrogen availability and thereby potentially improving plant growth and resilience against pests and pathogens. Also, Beesigamukama et al. (2020) reported that the black soldier fly frass may favor growth and nutritional uptake in maize and increase chlorophyll concentration, which further contributes to plant vigor under stress conditions.

Frass also increases the beneficial microbes in soil, which enhances structure and fertility of the soil, helping plan health. For instance, cricket frass can act as an elicitor for microorganisms to fix nitrogen and solubilize nutrients within soil, supporting plant strength (Ferruzca-Campos et al., 2023). Ogaji et al. (2022) illustrated that the cricket frass improved physical and chemical properties of soil to enhance spring onion growth, implying that frass may support a more favorable soil microbiome for plant stress tolerance.

Beyond nutrients and microbes, frass may improve plant defenses. Gao et al. (2022) stated that frass from some insect larvae can induce plant defense but also induce secondary metabolites that would help in deterring herbivores. This suggests that frass might aid plants in combating pest and pathogen attacks by enhancing their innate resistance.

Nevertheless, some limitations and variations exist in the body of literature exploring the mitigating potential of frass as an abiotic stressor. The inconsistency seen across studies regarding the impact of frass is caused by the variability found in nutrient composition, which can greatly differ based on diet. These findings point towards the necessity for standardization of frass quality in agricultural use. Moreover, even though frass is a potential agent for plant promotion and resistance, its effect on soil fertility and overall ecosystem functioning over the long term has not been as extensively studied. Hence, its possibilities and drawbacks require further investigation.

Challenges, Limitations, and Future Directions

Despite the potential benefits of insect frass, several challenges remain in the utilization of insect frass as a standard agricultural amendment, namely its nutrient composition variability, cost issues, and research gap. Frass nutrient composition can vary with insect species, diets as well as the conditions under which insects are reared. For example, black soldier fly (BSF) larvae produce frass with a higher moisture content makes its utility and storage more difficult (Praeg, 2023). The inconsistency from variable composition of insects as different species will excrete frass with varying physicochemical attributes has made farmers achieve unpredictable outcomes (Beesigamukama et al., 2022). Cost represents another important factor. Due to aspects related to insect rearing, processing, and transportation, frass is often very expensive compared with conventional fertilizers and consequently the economic feasibility of this resource as a fertilizer is restricted. Although frass has shown potential to boost plant growth and production, the market for it is still under development, and farmers will be reluctant to adopt (or try) frass without demonstrated effectiveness of specific products on their part (Ahmad, 2024).

Crucially, big gaps in research about what the best application rate is, what the environmental effects are, and long-term effects remain. Although frass can provide certain benefits, excessive application may be detrimental to plant growth due to high ammonium and salt content (Fuhrmann et al., 2022), with still little known about the impact on soil health or microbial communities over the long-term (Looveren et al., 2021).

Further studies should be conducted to investigate the impact of soil frass on other crop species, varieties, climate zones, and in different soil-type interactions. Since nutrient variability has great potential to be reduced by standardizing frass production, the assurance of constant quality can be facilitated. Field trials to generate positive effects in real agricultural situations and recommend its use are also required for the final validation of frass.

Conclusion

The ability of *Tenebrio molitor L.* (yellow mealworm) frass to be an environmentally friendly soil amendment and biotic stress mitigator is a promising trait that needs further investigation in terms of discovering its role as a sustainable agricultural component. With the composition of nutrients such as Nitrogen, Phosphorous, and Potassium, it increases soil health, helps in plant growth, and authorizes microbial diversity to thrive which is essential for biological fertility. Another point is that frass induces plant defense responses, enhancing resistance to pests and disease, which is an important aspect of sustainable pest control.

Although it has great potential, several roadblocks that remain to be overcome are associated with uncertainty in nutrient composition levels, which may arise because of differences in the insect diet or rearing conditions and can cause variation in results. More research is needed to evaluate long-term environmental consequences, optimal application rates, and test field trials on a range of crops, soil types, and climates. In future studies, economic comparisons between frass and conventional fertilizers will have to be assessed to achieve full integration of frass application into current agricultural practices.

References

Ahmad, N. (2024). Utilizing insect frass (faecal matter): a sustainable approach to organic fertilization in agriculture. International Journal of Environment and Climate Change, 14(4), 386-396. https://doi.org/10.9734/ijecc/2024/v14i44125

Beesigamukama, D., Mochoge, B., Korir, N., Fiaboe, K., Nakimbugwe, D., Khamis, F., … & Tanga, C. (2020). Exploring black soldier fly frass as novel fertilizer for improved growth, yield, and nitrogen use efficiency of maize under field conditions. Frontiers in Plant Science, 11. https://doi.org/10.3389/fpls.2020.574592

Beesigamukama, D., Subramanian, S., & Tanga, C. (2022). Nutrient quality and maturity status of frass fertilizer from nine edible insects. Scientific Reports, 12(1). https://doi.org/10.1038/s41598-022-11336-z

Dulaurent, A., Daoulas, G., Faucon, M., & Houben, D. (2020). Earthworms (Lumbricus terrestris L.) mediate the fertilizing effect of frass. Agronomy, 10(6), 783. https://doi.org/10.3390/agronomy10060783

Ferruzca-Campos, E., Rico-Chávez, A., Guevara-González, R., Urrestarazu, M., Cunha-Chiamolera, T., Reynoso-Camacho, R., … & Guzmán-Cruz, R. (2023). Biostimulant and elicitor responses to cricket frass (Acheta domesticus) in tomato (Solanum lycopersicum L.) under protected conditions. Plants, 12(6), 1327.

Fuhrmann, A., Wilde, B., Conz, R., Kantengwa, S., Konlambigue, M., Masengesho, B., & Hartmann, M. (2022). Residues from black soldier fly (Hermetia illucens) larvae rearing influence the plant-associated soil microbiome in the short term. Frontiers in Microbiology, 13. https://doi.org/10.3389/fmicb.2022.994091

Gao, Z., Ju, X., Yang, M., Xue, R., Li, Q., Fu, K., & Wang, J. (2022). Colorado potato beetle exploits frass-associated bacteria to suppress defense responses in potato plants. Pest Management Science, 78(9), 3778-3787.

Gärttling, D., & Schulz, H. (2021). Compilation of black soldier fly frass analyses. Journal of Soil Science and Plant Nutrition, 22(1), 937-943. https://doi.org/10.1007/s42729-021-00703-w

Gärttling, D., Kirchner, S., & Schulz, H. (2020). Assessment of the N- and P-fertilization effect of black soldier fly (Diptera: Stratiomyidae) by-products on maize. Journal of Insect Science, 20(5). https://doi.org/10.1093/jisesa/ieaa089

Gebremikael, M., Wickeren, N., & Hosseini, P. (2022). The impacts of black soldier fly frass on nitrogen availability, microbial activities, C sequestration, and plant growth. Frontiers in Sustainable Food Systems, 6. https://doi.org/10.3389/fsufs.2022.79595

Hénault-Éthier, L., Reid, B., Hotte, N., Paris, N., Quinche, M., Lachance, C., … & Vandenberg, G. (2023). Growth trials on vegetables, herbs, and flowers using mealworm frass, chicken manure, and municipal compost. ACS Agricultural Science & Technology, 3(3), 249-259. https://doi.org/10.1021/acsagscitech.2c00217

Houben, D., Daoulas, G., & Dulaurent, A. (2021). Assessment of the short-term fertilizer potential of mealworm frass using a pot experiment. Frontiers in Sustainable Food Systems, 5. https://doi.org/10.3389/fsufs.2021.714596

Houben, D., Daoulas, G., Faucon, M., & Dulaurent, A. (2020). Potential use of mealworm frass as a fertilizer: Impact on crop growth and soil properties. Scientific Reports, 10(1). https://doi.org/10.1038/s41598-020-61765-x

Looveren, N., Vandeweyer, D., & Campenhout, L. (2021). Impact of heat treatment on the microbiological quality of frass originating from black soldier fly larvae (Hermetia illucens). Insects, 13(1), 22. https://doi.org/10.3390/insects13010022

Nogalska, A. (2024). Farmed insect frass as a future organic fertilizer. Applied Sciences, 14(6), 2380.

Nyanzira, A., Machona, O., Matongorere, M., Chidzwondo, F., & Mangoyi, R. (2023). Analysis of frass excreted by Tenebrio molitor for use as fertilizer. Entomology and Applied Science Letters, 10(1), 29-37. https://doi.org/10.51847/xbw1oofqxn

Ogaji, S., Watako, A., Nyongesah, J., & Bulli, P. (2022). Effects of cricket frass biofertilizer on growth of spring onion (Allium fistulosum L.) and physicochemical properties of soil. Journal of Modern Agriculture and Biotechnology, 1(3), 14. https://doi.org/10.53964/jmab.2022014

Praeg, N. (2023). Frass fertilizers from mass-reared insects: Species variation, heat treatment effects, and implications for soil application. BioRxiv. https://doi.org/10.1101/2023.09.28.559882

Przemieniecki, S. (2024). The effects of frass and vermicompost fertilization on the biometrical parameters of plant and soil quality, and the rhizobiome, in red beet (Beta vulgaris L.) cultivation. Applied Sciences, 14(13), 5539. https://doi.org/10.3390/app14135539

Shadeed, S., Judeh, T., & Riksen, M. (2020). Rainwater harvesting for sustainable agriculture in high water-poor areas in the west bank, palestine. Water, 12(2), 380. https://doi.org/10.3390/w12020380

Wantulla, M., Zadelhoff, K., Loon, J., & Dicke, M. (2022). The potential of soil amendment with insect exuviae and frass to control the cabbage root fly. Journal of Applied Entomology, 147(3), 181-191. https://doi.org/10.1111/jen.13097

Effects of organic wastes on permeability ratio

Nutullah ÖZDEMİR*, Zerrin CİVELEK

Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Nutullah ÖZDEMİR

nutullah@omu.edu.tr

Abstract

This research was carried out to determine the effects of application of organic materials of different origins (barnyard manure, wheat straw, vetch straw and garbage compost) to 3 different textured soils (SCL, C, CL) under greenhouse conditions on soil properties and permeability ratio. The research was carried out in a factorial arrangement as a greenhouse study. In the study where 5 kg pots were used, organic materials were applied at 5 different doses (%0.0, 0.5, 1.0, 2.0 and 4.0). In the study carried out during the ten-week incubation phase, the greenhouse temperature varied between 23±2 °C. The surface soil samples used were fine-textured and medium-fine-textured, medium and low lime content, low organic matter content and alkalinity problem free soils. As a result, it was determined that organic material applications statistically significantly reduced the permeability ratio values of soils that were initially sensitive to erosion and were in three different texture classes. The activities of organic residues varied among themselves and according to soil texture classes. The effectiveness of urban waste compost in this regard was lower than that of barnyard manure, wheat straw and vetch straw.

Keywords: Soil texture, permeability ratio, susceptibility to erosion, organic wastes

Introduction

Improving soil quality parameters is very important in terms of meeting the needs of increasing population and developing economies, controlling environmental pollution, developing soil and water resources and sustainability of agricultural production. Organic materials have significant effects or contributions in improving soil quality parameters and creating a more resistant structure against erosion (Lima et al., 2009; Murphy, 2015; Voltr et al., 2021; Sithole et al., 2019; Özdemir and Desti, 2024). The organic matter content of agricultural soils varies depending on the intensity of land use and the type and amount of organic materials added to the soil (Dominy et al., 2002; Haghighi et al., 2010; Obalum et al., 2017; Özdemir and Desti, 2024). For this purpose, different scientists have used different amounts of farm manure (Dixit and Gupta, 2000; Khan et al., 2010; Rayne and Aula, 2020), grain residues (Blanco-Canqui and Lal, 2007; Hu et al., 2021; Cui et al., 2022), green manure (Tejada et al., 2008; Müjdeci, et al., 2020; Ma et al., 2021), garbage compost (Giannakis et al., 2014; Angin et al., 2013) and some other organic materials (Barzegar et al., 2002; Wang et al., 2013).

The change in the physical structure is an important indicator in revealing the effects of soil management and land use practices on soil degradation (Gil-Sotres et al., 2005; Tale and Ingole, 2015; Assenato et al., 2020). Soil organic matter significantly affects physical quality parameters. Therefore, different researchers emphasize the functions of transforming mineral particles into aggregates, protecting soil aggregates against rapid decomposition of organic matter by microorganisms, and acting as a reservoir for C and other important substances while examining the role of soil organic matter (Legaz et al., 2017; Chenu et al., 2019). On the other hand, soil organic matter is also a stimulator of soil biota (Doran et al., 2018; Kotroczó and Fekete, 2020), and a protector of some other soil physico-chemical conditions such as cation exchange capacity (CEC) and pH (Weil and Magdoff, 2004; Ghimire et al., 2017).

Annabi et al. (2004) conducted a study under laboratory and field conditions. After examining the effect of conventional farm manure and two types of municipal waste compost on structural stability in a loamy soil and the relationship of this effect with microbial activity, the researchers emphasized that there are close relationships between soil organic matter and structural stability and the decomposition rate of added fertilizer.

This study was carried out to investigate the effects of organic residues such as barnyard manure, wheat straw, vetch straw and garbage compost added to the soil under laboratory conditions on the permeability ratio of the soil (sandy clay loam, clay, clay loam) and hence on its susceptibility to erosion.

Material and Methods

The study was carried out under greenhouse conditions using surface (0-20 cm) soil samples of three different texture classes. Organic materials were obtained from different institutions.

Table 1. Some properties of soils and organic materials

Soil properties	Soils			
		SCL (1)	C (2)	CL(3)
Sand, %		45.10	16.14	28.05
Silt, %		22.88	23.64	33. 20
Clay, %		32.02	60.22	38.75
pH		7.56	8.15	8.20
Lime, %		0.42	1.13	10.30
Organic matter, %		1.52	1.43	1.50
Cation exchange capacity (me/100 g)		34.30	57.23	41.25
Exchangeable sodium, %		2.21	1.73	2.42
Clay ratio		1.95	0.66	1.55
Properties	Organic waste			
	Barnyard manure	Wheat straw	Vetch straw	Garbage compost*
Total O.M, %	68.47	87.35	86.35	24.95
Total-C,%	40.04	51.02	49.77	14.46
Total-N, %	1.68	0.55	2.19	0.92
Total-P_2O_5, %	0.10	0.40	0.18	0.08
Total-K_2Ox10^{-1}, %	0.21	0.15	0.16	0.19
Total-Ca, %	1.94	1.24	1.13	1.66
Total-Mg, %	0.44	0.41	0.23	0.38
Total-Nax10^{-2}, %	0.59	0.16	0.15	0.60
C/N ratio	23.55	91.11	22.42	15.89

*: maximum grain diameter 10 mm; coarse sand (0.2-2 mm) 22%; stone, gravel, glass etc. (2-10mm)

In the greenhouse study conducted in factorial design, four different organic materials were added to each of the three soil texture groups in five different doses (3x5x4) x3. In the greenhouse study, shade-dried soil samples sieved through a 2 mm sieve were used and mixed with 0.0, 0.5, 1.0, 2.0 and 4.0 % of barnyard manure, wheat straw, vetch straw and garbage compost. The mixtures were transferred to 25 cm x 25 cm x 10 cm sheet metal boxes. Tap water was added drop by drop to the mixtures in the boxes until they reached the field capacity and then left to incubate. During this period, the boxes were weighed periodically every day and when 50% of the available moisture was used up, tap water was added to the boxes until they reached the field capacity again. Incubation was continued for 10 weeks and the greenhouse temperature was kept at 23±2°C during this period. After the incubation period, soil samples were hand crumbled and transferred to the laboratory.

Grain size distribution of the soils was determined by sedimentation method (Demiralay, 1993); soil pH was determined by pH meter in 1:2.5 soil-water suspension (Kacar, 1994); lime content by volume (Kacar, 1994); organic matter content by Walkley-Black method (Kacar, 1994); cation exchange capacity by Bower method (Kacar, 1994). Some properties of barnyard manure, wheat straw, vetch straw and garbage compost were determined based on (Harris, 1970). The permeability ratio values of the soils were determined by using air and water permeability values measured on degraded soil samples (Özdemir, 2013). SPSS computer package program was used to evaluate the data.

Results and Discussion

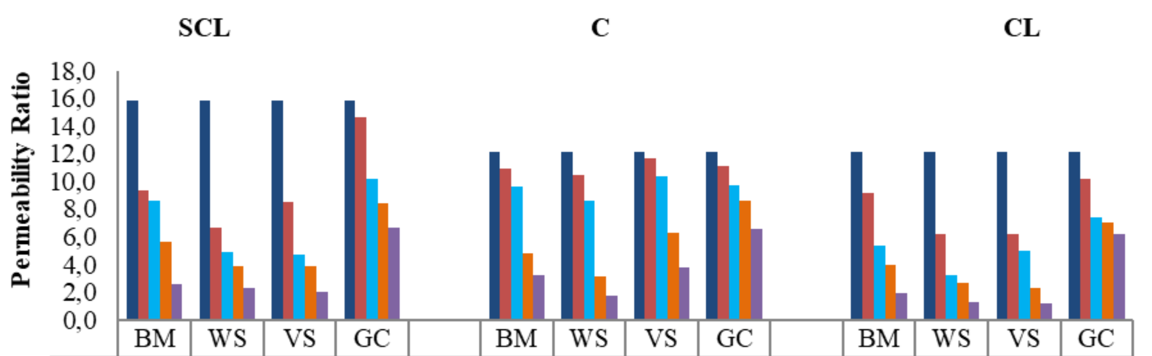
Soil properties

Some physical and chemical properties of the soils used in the study determined before the experiment are presented in Table 1. As can be seen from this table, the soils are fine and moderately fine textured. Soil number two (clay) is fine textured, while soils number one (sandy clay loam) and number three (clay loam) are moderately fine textured. The pH (1:2.5) values of the soils are between 7.6 and 8.2 and the soils are slightly alkaline (sample number 1, 7.56) and moderately alkaline (sample number 2, 8.15 and sample number 3, 8.20) in terms of reaction. The lime content of the soils was very low (sample 1, 0.42% and sample 2, 1.13%) and moderate (sample 3, 10.30%). Organic matter content was low in all three soils, around 1.5%. The cation exchange capacities of the soils ranged between 34 and 57 me/100 g and this value was highest in sample number 2 with 60% clay content. The percentage of exchangeable sodium in the soils is below 15 and there is no alkalinity problem (Mallah and Bagheri-Bodaghabadi, 2022).

By utilizing the textural properties of the soils, as a first approach, a preliminary judgment can be made about their stability and erodibility. If the soils selected for the experiment are evaluated based on silt/clay ratio, they can be characterized as unstable soils (Bryan, 1968, Özdemir, 2013). When the clay ratio ((sand + loam)/clay) of sample number 2 is taken into consideration, it can be said that it is more resistant to erosion than the others. The clay ratio values of these soils with the same organic matter contents are 1.95, 0.66 and 1.55 respectively. A small clay ratio (Bryan, 1968; Morgan 2009; Özdemir, 2013) indicates that the soil is more resistant to erosion. The cation exchange capacity of the same soil is the highest. This gives the impression that the soil in question is less susceptible to erosion.

Permeability Ratio

The permeability ratio values (average of 3 values) obtained by mixing different levels of barnyard manure, wheat straw, vetch straw and garbage compost are given in Figure 1. It can be seen from this plot that all four organic materials significantly decreased permeability ratio values of the soils depending on the level of application. This decreased was higher in soil sample number 1 which had low stability (control 15,8). The statistical analysis results showed that the organic materials (barnyard manure, wheat straw, vetch straw, and garbage compost) and the applied levels caused significant differences in the permeability ratio ($p<0.01$), and the interaction between soil and organic materials was also found to be significant.



	BM	WS	VS	GC		BM	WS	VS	GC		BM	WS	VS	GC
0.0	15,8	15,8	15,8	15,8		12,1	12,1	12,1	12,1		12,1	12,1	12,1	12,1
0.5	9,3	6,7	8,5	14,6		10,9	10,5	11,7	11,1		9,2	6,2	6,2	10,2
1.0	8,6	4,9	4,7	10,2		9,6	8,6	10,4	9,7		5,4	3,2	5,0	7,4
2.0	5,6	3,9	3,9	8,4		4,8	3,1	6,3	8,6		4,0	2,7	2,3	7,0
4.0	2,6	2,3	2,0	6,7		3,2	1,7	3,8	6,6		1,9	1,3	1,2	6,2

Figure 1. Change in permeability ratio values of soils incorporated with organic materials at different levels (%)

The ratio of the soil's air permeability to its water permeability can be used as a good measure of its structural stability. This ratio reflects the deterioration in structure as a result of wetting, and the greater the ratio, the less stable it becomes. The permeability ratio varies between 2 and 3 in stable soils, between 3 and 50 in normal field soils, and is much greater in unstable soils (Reeve, 1965; Özdemir 2013). The permeability ratio value of 15.8 in the SCL textured control (without organic material applied) soil sample was reduced to between the limit values given for stable soils (2 and 3) at 4% levels of applied manure, wheat straw and vetch straw, but compost was not sufficient to reduce it to this range (Figure 1). In the C textured sample with a permeability ratio of 12.1, the 4% level of wheat straw reduced the permeability ratio value to the limit values given for stable soils. In this soil, other organic materials and their levels approached the given limit values (Figure 1). Again, in the CL textured sample with a permeability ratio of 12.1 (without fertilizer application), the 4% level of barnyard manure and the 2% levels of wheat and vetch straw reduced the permeability ratio value of the soil to the predicted limit values, ensuring that the soil was stable against water.

Conclusion

In this study conducted under laboratory conditions, organic materials such as barnyard manure, wheat straw, vetch straw and garbage compost mixed into the soils decreased permeability ratio in the experimental soils, improved some physical and mechanical properties and reduced the susceptibility of the soils to erosion. In this respect, the efficacy of garbage compost was lower.

References

Angin, I., Aksakal, E. L., Oztas, T., Hanay, A., 2013. Effects of municipal solid waste compost (MSWC) application on certain physical properties of soils subjected to freeze–thaw. Soil and Tillage Research, 130, 58-61.

Annabi, M., Houot, S., Poitrenaud, M., Rampon, J. N., Gaillard, H., Le Bissonnais, Y., 2004. Effect of organic amendments on soil aggregate stability. Sustainable Organic Waste Management for Environmental Protection and Food Safety. Ramiran, 2004, 51-54.

Assennato, F., Di Leginio, M., d'Antona, M., Marinosci, I., Congedo, L., Riitano, N., Munafò, M., 2020. Land degradation assessment for sustainable soil management. Italian Journal of Agronomy, 15(4), 299-305.

Barzegar, A. R., Yousefi, A., Daryashenas, A., 2002. The effect of addition of different amounts and types of organic materials on soil physical properties and yield of wheat. Plant and soil, 247(2), 295-301.

Blanco-Canqui, H., & Lal, R., 2007. Impacts of long-term wheat straw management on soil hydraulic properties under no-tillage. Soil Science Society of America Journal, 71(4), 1166-1173.

Bryan, R.B., 1968. The development, use and efficiency of indices of soil erodibility. Geoderma, 2, 5-25.

Chenu, C., Angers, D. A., Barré, P., Derrien, D., Arrouays, D., Balesdent, J., 2019. Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. Soil and Tillage Research, 188, 41-52.

Cui, H., Luo, Y., Chen, J., Jin, M., Li, Y., Wang, Z., 2022. Straw return strategies to improve soil properties and crop productivity in a winter wheat-summer maize cropping system. European Journal of Agronomy, 133, 126436.

Demiralay, İ., 1993. Toprak fiziksel analizleri. Atatürk Üniversitesi Ziraat Fakültesi Yayınları, 143, 13-19.

Dixit, K. G., & Gupta, B. R., 2000. Effect of farmyard manure, chemical and biofertilizers on yield and quality of rice (Oryza sativa L.) and soil properties. Journal of the Indian Society of Soil Science, 48(4), 773-780.

Dominy, C., Haynes, R., Van Antwerpen, R., 2002. Loss of soil organic matter and related soil properties under long-term sugarcane production on two contrasting soils. Biology and Fertility of Soils, 36, 350-356.

Doran, J. W., Jones, A. J., Arshad, M. A., Gilley, J. E., 2018. Determinants of soil quality and health. In Soil quality and soil erosion (pp. 17-36). CRC Press.

Ghimire, R., Machado, S., Bista, P., 2017. Soil pH, soil organic matter, and crop yields in winter wheat–summer fallow systems. Agronomy Journal, 109(2), 706-717.

Giannakis, G. V., Kourgialas, N. N., Paranychianakis, N. V., Nikolaidis, N. P., Kalogerakis, N., 2014. Effects of municipal solid waste compost on soil properties and vegetables growth. Compost science & utilization, 22(3), 116-131.

Gil-Sotres, F., Trasar-Cepeda, C., Leirós, M. C., Seoane, S., 2005. Different approaches to evaluating soil quality using biochemical properties. Soil biology and biochemistry, 37(5), 877-887.

Haghighi, F., Gorji, M., Shorafa, M., 2010. A study of the effects of land use changes on soil physical properties and organic matter. Land Degradation & Development, 21(5), 496-502.

Harris, L.E., 1970. Nutrition research techniques, for domestic and wild animal. An Intern. Record System and Procedures, for Analizing Samples, Logan, Utah, 1.

Hu, Y., Sun, B., Wu, S., Feng, H., Gao, M., Zhang, B., Liu, Y., 2021. After-effects of straw and straw-derived biochar application on crop growth, yield, and soil properties in wheat (Triticum aestivum L.)-maize (Zea mays L.) rotations: A four-year field experiment. Science of the Total Environment, 780, 146560.

Kacar, B., 1994. Bitki ve toprağın kimyasal analizleri. Ankara Üniversitesi Ziraat Fakültesi Eğitim, Araştırma ve Geliştirme Vakfı.

Khan, N. I., Malik, A. U., Umer, F., Bodla, M. I., 2010. Effect of tillage and farm yard manure on physical properties of soil. International Research Journal of Plant Science, 1(4), 75-82.

Kotroczó, Z., & Fekete, I., 2020. Significance of soil respiration from biological activity in the degradation processes of different types of organic matter. DRC Sustainable Future: Journal of Environment, Agriculture, and Energy, 1(2), 171-179.

Legaz, B. V., De Souza, D. M., Teixeira, R. F., Antón, A., Putman, B., Sala, S., 2017. Soil quality, properties, and functions in life cycle assessment: an evaluation of models. Journal of cleaner production, 140, 502-515.

Lima, D. L., Santos, S. M., Scherer, H. W., Schneider, R. J., Duarte, A. C., Santos, E. B., Esteves, V. I., 2009. Effects of organic and inorganic amendments on soil organic matter properties. Geoderma, 150(1-2), 38-45.

Ma, D., Yin, L., Ju, W., Li, X., Liu, X., Deng, X., Wang, S., 2021. Meta-analysis of green manure effects on soil properties and crop yield in northern China. Field Crops Research, 266, 108146.

Mallah, S., & Bagheri-Bodaghabadi, M., 2022. Towards a global soil taxonomy and classification tool for predicting multi-level soil hierarchy. Modeling Earth Systems and Environment, 8(2), 1505-1517.
Morgan, R. P. C., 2009. Soil erosion and conservation. John Wiley & Sons.
Murphy, B. W., 2015. Impact of soil organic matter on soil properties—a review with emphasis on Australian soils. Soil Research, 53(6), 605-635.
Müjdeci, M., Alaboz, P., Demircioğlu, A. C., 2020. The effects of farmyard manure and green manure applications on some soil physical properties. Yuzuncu Yıl University Journal of Agricultural Sciences, 30(1), 9-17.
Obalum, S. E., Chibuike, G. U., Peth, S., Ouyang, Y., 2017. Soil organic matter as sole indicator of soil degradation. Environmental monitoring and assessment, 189, 1-19.
Özdemir N., 2013. Toprak ve Su Koruma. OMÜ Ziraat Fakültesi Ders kitabı No. 22. Samsun.
Özdemir, N., & Desti, E. B., 2024. Arazi kullanım şekli ve bazı toprak özelliklerinin organik madde içeriğine etkileri. Toprak Bilimi ve Bitki Besleme Dergisi, 12(1), 20-26.
Rayne, N., & Aula, L., 2020. Livestock manure and the impacts on soil health: A review. Soil Systems, 4(4), 64.
Reeve, R.C., 1965. Air-to-water permeability ratio. In C.A. Black (ed). Methods of soil analysis Part I, Agronomy No 9.
Sithole, N. J., Magwaza, L. S., Thibaud, G. R., 2019. Long-term impact of no-till conservation agriculture and N-fertilizer on soil aggregate stability, infiltration and distribution of C in different size fractions. Soil and Tillage Research, 190, 147-156.
Tale, K. S., & Ingole, S., 2015. A review on role of physico-chemical properties in soil quality. Chemical Science Review and Letters, 4(13), 57-66.
Tejada, M., Gonzalez, J. L., García-Martínez, A. M., Parrado, J., 2008. Application of a green manure and green manure composted with beet vinasse on soil restoration: effects on soil properties. Bioresource technology, 99(11), 4949-4957.
Voltr, V., Menšík, L., Hlisnikovský, L., Hruška, M., Pokorný, E., Pospíšilová, L., 2021. The soil organic matter in connection with soil properties and soil inputs. Agronomy, 11(4), 779.
Wang, F., Tong, Y. A., Zhang, J. S., Gao, P. C., Coffie, J. N., 2013. Effects of various organic materials on soil aggregate stability and soil microbiological properties on the Loess Plateau of China.
Weil, R. R., & Magdoff, F., 2004. Significance of soil organic matter to soil quality and health. Soil organic matter in sustainable agriculture, 1-43.

Soil Persistence of the imidazolinone herbicides-challenges and opportunities

Hussein SADDAM *, Dobrinka BALABANOVA

Department of Plant Physiology, Biochemistry, and Genetics. Agricultural University – Plovdiv, Bulgaria

***Corresponding Author**

Hussein SADDAM

husseinraaz41@gmail.com

Abstract

Effective weed control is crucial for high productivity and profitability in crop cultivation, where the most efficient method is chemical control using herbicide application. Typically, herbicides are designed to break down in the environment, but some of them may persist in the soil and pose significant risks to subsequent crops. Herbicides from the imidazolinone (IMI) group are widely used in a number of imidazolinone-resistant crops due to their high efficiency and environmentally friendly profile. Although imidazolinone herbicides are used in low doses, they are characterized by a slow degradation rate, leading to their soil persistence for up to 2 years. The residual amounts of IMI herbicides may significantly damage subsequent susceptible crops in the crop rotation, leading to reduced growth and productivity. The current review aims to summarize the recent research on the residual effects of IMI herbicides and the opportunities for ameliorating phytotoxicity symptoms in the following crops.

Keywords: Herbicide degradation, Imazamox, Imidazolinone herbicides, Phytotoxicity, Residual herbicides, Soil persistence

Introduction

Weed control is one of the main factors for highly productive and profitable farming, where the most effective methods are chemical control and herbicide application. Herbicides are an essential part of present-day agriculture worldwide because of their effective control of noxious weed species. Typically, herbicides are designed to break down in the environment, but some may persist in the soil and pose significant risks to the soil environment and subsequent crops (Hess et al., 2010). Another factor that increases the residual amount of herbicides in the soil is that not all the applied herbicides reach the target plants. Only about 5 % of the herbicides fall directly on the weeds, whereas about 95 % enter the soil or get exposed to non-target organisms (Miller, 2004).

Consequences of Soil Herbicide Residues

The residual amounts of herbicides in the soil may cause phytotoxic effects on subsequent crops, such as stunted growth and chlorosis, resulting in reduced yield and productivity (Vasic et al., 2019). Furthermore, the retention of herbicides in the soil can adversely impact the environment, such as soil and water pollution, decreased biodiversity, and a decline in soil microorganisms (Juhler et al., 2001; Song et al., 2013), disrupting nutrient cycling and reducing soil fertility (Rose et al., 2016). These chemicals can inhibit microbial metabolic processes, such as the synthesis of amino acids and nitrogen metabolism (Thiour-Mauprivez et al., 2019). Additionally, herbicide residues can alter the composition of microbial communities and favor the thriving of species resistant to herbicides while reducing the population of species sensitive to herbicides, which may destabilize soil ecosystems (Aguiar et al., 2020). The long-term consequences of soil exposure to herbicides can negatively affect soil structure, reduce soil organic matter decomposition, and impair the ability of the soil to maintain plant mineral nutrition, thereby affecting crop productivity and ecosystem resilience (Ruuskanen et al., 2023).

Herbicide Persistence in Soil

The soil persistence of the herbicides is the time that herbicide molecules remain active in the soil and is also known as "soil residual life". The residual activity of herbicide molecules is often described in terms of "half-life," which describes the time required for the dissipation of one-half of the initial amount of applied herbicide (Colquhoun, 2006). The half-life varies by herbicide, ranging from a few days to a few years. Several factors determine the duration of herbicide persistence, which can be summarized into three groups: soil factors, climatic conditions, and herbicidal properties. Soil factors influencing herbicide persistence include soil composition and microbial activity (Curran, 2016). The microorganisms account for a large portion of herbicide degradation in soil. The soil microflora, like bacteria, fungi, and algae, may use the herbicide as a carbon source. Therefore, the conditions that support high microflora populations and activity favor rapid herbicide degradation in soil (Colquhoun, 2006). The climatic factors involved in herbicide degradation rate are moisture and temperature. The chemical characteristics of the herbicide molecule also affect its persistence. These properties include vapor pressure, water solubility, and the molecule's ability for chemical or microbial breakdown (Curran, 2016).

Imidazolinone Herbicides – Agriculture Benefits, Degradation and Soil Persistence

Imidazolinone herbicide family (IMI) includes imazapyr, imazapic, imazethapyr, imazamox, imazamethabenz, and imazaquin (Shaner and O'Connor, 1991). IMI herbicides function by inhibiting the activity of the acetohydroxyacid synthase activity (AHAS, EC 2.2.1.6), also referred to as acetolactate synthase (ALS), catalyzing the first step of the essential branched-chain amino acids (Shaner & Singh, 1997). The IMI herbicides are widely applied thanks to their high efficacy in controlling grasses and broad-leaved weeds. In addition, these herbicides can also control weeds closely related to the crop itself and some problematic parasitic weeds such as broomrape (Tan et al., 2005). Moreover, they are characterized by low application rates and low mammalian toxicity (Pfenning et al., 2008). They are used in the Clearfield® technology as a post-emergence weed control option in imidazolinone-resistant crops, including sunflower, rapeseed, wheat, and rice (Pfenning et al., 2008; Milan et al., 2017).

Although imidazolinone herbicides are used in low doses, they are characterized by a slow degradation rate (Shaner, 2014), leading to their persistence in the soil for up to 2 years (Marchesan et al., 2010). Imidazolinone herbicides tend to have a long half-life and thus remain active in the soil for a long time. The half-life of imazamox in the soil varies between 17 and 92 days (Vischetti et al., 2002) or even up to 180 days, depending on soil conditions (Hess et al., 2010). The literature highlights that these herbicides may not immediately break down or convert into less harmful compounds but may remain active in the soil for a long time (Kanissery & Sims, 2011). The persistence of imidazolinone herbicides in soil may injure subsequent susceptible crops in the crop rotation (Pannacci et al., 2006; Hess et al., 2010; Liu et al., 2016). In addition, the IMI residues, when left in the environment, may also damage the non-target plants (Alister & Kogan, 2005; Liu et al., 2016).

The degradation of imidazolinone herbicides in the soil is primarily due to microbial activity (Liu et al., 2016). According to some reports, the degradation of imidazoline herbicides in sterile soil exceeds 800 days (Wu et al., 2017). This additionally emphasizes the central role of microbial processes and the importance of microbial populations in the soil degradation of these herbicides. Aichele and Penner (2005) considered the optimal soil moisture and temperatures as the main factors accelerating the IMI degradation by soil microflora. In addition to the abovementioned, Liu et al. (2016) highlighted the significance of organic matter content and soil pH on the IMI degradation rate. Other studies also emphasize the influence of climatic conditions, soil clay and organic matter content, soil humidity, and cation exchange capacity on the IMI degradation in soil (Vasic et al., 2019).

Microbial Soil Improvers – New Opportunity for Herbicide Breakdown

Based on the abovementioned evidence, we may assume that improving the conditions for optimal development and activity of soil microflora would enhance the effectiveness of herbicide degradation. This can be achieved mainly in two ways: by carrying on optimal soil moisture or by introducing products that would support the development of soil microflora, such as plant biostimulants or soil improvers. Maintaining optimal soil moisture can only be achieved by irrigating the arable lands, which is practically impossible. Several publications have reported an ameliorative effect on herbicide-damaged plants as a result of additional treatment with plant biostimulants (Zarzecka et al., 2020; Gehrke et al., 2021). Rodríguez-Morgado et al. (2014) reported a stimulating effect on the enzymatic activity of soil microflora after the application of protein hydrolysate in soils with residual amounts of the herbicide oxyfluorfen. In general, the effects of the application of biostimulants and, in particular, soil improvers on plants and soils with phytotoxic residues of herbicides have not been studied. The optimal performance of the soil microflora is an essential factor for effective IMI degradation in soil and reducing the residual phytotoxic symptoms on rotational crops.

Conclusion

Balancing herbicide use with the need to maintain soil health and ecosystem resilience is crucial for sustaining both agricultural productivity and environmental sustainability. Applying biostimulants and soil improvers is a valuable tool to reduce the negative impacts of herbicide residues on crops and soil properties. These methods may enhance the breakdown of herbicides, reduce the phytotoxic effects of the herbicide residues, and improve soil health and microbial activity. Healthy soil produces healthy foods, so utilizing new soil care strategies that enhance soil performance is essential for the scientific and agronomy community. Whether this can be achieved through new tools, such as soil improvers and plant biostimulants, remains a relevant and ongoing issue that calls for future research.

References

Aguiar, L.M., Dos Santos, J.B., Barroso, G.M., Laia, M.L. de, Gonçalves, J.F., da Costa, V.A.M., Brito, L.A., 2020. Influence of 2, 4-D residues on the soil microbial community and growth of tree species. International Journal of Phytoremediation, 22(1), 69–77.

Aichele, T.M., Penner, D., 2005. Adsorption, desorption, and degradation of imidazolinones in soil. Weed Technology, 19(1), 154–159.

Colquhoun, J., 2006. Herbicide persistence and carryover. Madison, WI: University of Wisconsin Extension A, 3819.

Curran, W.S., 2016. Persistence of herbicides in soil. Crops & Soils, 49(5), 16–21.

Gehrke, V.R., Fipke, M.V., de Avila, L.A., Camargo, E.R., 2021. Understanding the opportunities to mitigate carryover of imidazolinone herbicides in lowland rice. Agriculture (Switzerland), 11(4).

Gerhards, R., Ouidoh, F.N., Adjogboto, A., Avohou, V.A.P., Dossounon, B.L.S., Adisso, A.K.D., Heyn, A., Messelhäuser, M., Santel, H.J., Oebel, H., 2021. Crop response to leaf and seed applications of the biostimulant ComCat® under stress conditions. Agronomy, 11(6), 1161.

Hess, F.G., Harris, J.E., Pendino, K., Ponnock, K., 2010. Imidazolinones. In Hayes' Handbook of Pesticide Toxicology (pp. 1853–1863). Elsevier.

Juhler, R.K., Sørensen, S.R., Larsen, L., 2001. Analysing transformation products of herbicide residues in environmental samples. Water Research, 35(6), 1371–1378.

Kanissery, R.G., Sims, G.K., 2011. Biostimulation for the Enhanced Degradation of Herbicides in Soil. Applied and Environmental Soil Science, 2011, 1–10.

Liu, C. guang, Yang, X., Lai, Y., Lu, H. gang, Zeng, W. min, Geng, G., Yang, F., 2016. Imazamox microbial degradation by common clinical bacteria: Acinetobacter baumannii IB5 isolated from black soil in China shows high potency. Journal of Integrative Agriculture, 15(8), 1798–1807.

Marchesan, E., Dos Santos, F.M., Grohs, M., De Avila, L.A., Machado, S.L.O., Senseman, S.A., Massoni, P.F.S., Sartori, G.M.S., 2010. Carryover of imazethapyr and imazapic to nontolerant rice. Weed Technology, 24(1), 6–10.

Milan, M., Ferrero, A., Fogliatto, S., De Palo, F., Vidotto, F., 2017. Imazamox dissipation in two rice management systems. The Journal of Agricultural Science, 155(3), 431–443.

Miller, G.T., 2004. Sustaining the earth/Thompson learning. Inc.

Pannacci, E., Onofri, A., Covarelli, G., 2006. Biological activity, availability and duration of phytotoxicity for imazamox in four different soils of central Italy. Weed Research, 46(3), 243–250.

Pfenning, M., Palfay, G., Guillet, T., 2008. The CLEARFIELD® technology–A new broad-spectrum post-emergence weed control system for European sunflower growers. Journal of Plant Diseases and Protection, 21, 649–654.

Rodríguez-Morgado, B., Gómez, I., Parrado, J., Tejada, M., 2014. Behaviour of oxyfluorfen in soils amended with edaphic biostimulants/biofertilizers obtained from sewage sludge and chicken feathers. Effects on soil biological properties. Environmental Science and Pollution Research, 21, 11027–11035.

Rose, M.T., Cavagnaro, T.R., Scanlan, C.A., Rose, T.J., Vancov, T., Kimber, S., Kennedy, I.R., Kookana, R.S., Van Zwieten, L., 2016. Impact of herbicides on soil biology and function. Advances in Agronomy, 136, 133–220.

Ruuskanen, S., Fuchs, B., Nissinen, R., Puigbò, P., Rainio, M., Saikkonen, K., Helander, M., 2023. Ecosystem consequences of herbicides: the role of microbiome. Trends in Ecology and Evolution, 38(1), 35–43.

Shaner, D.L., 2014. Herbicide Handbook (10th edn, Lawrence, KS: Weed Science Society of America. Pp, 13, 177–178.

Shaner, D., O'Connor, S., 1991. The Imidazolinone Herbicides (1991) (1st ed.). CRC Press. https://doi.org/10.1201/9780203709993

Shaner, D.L., Singh, B.K., 1997. Herbicide Activity: Toxicology, Biochemistry and Molecular Biology. By RM Roe, JD Burton & RJ Kuhr, 105, 69–110.

Tan, S., Evans, R.R., Dahmer, M.L., Singh, B.K., Shaner, D.L., 2005. Imidazolinone-tolerant crops: history, current status and future. Pest Management Science: Formerly Pesticide Science, 61(3), 246–257.

Thiour-Mauprivez, C., Martin-Laurent, F., Calvayrac, C., Barthelmebs, L., 2019. Effects of herbicide on non-target microorganisms: towards a new class of biomarkers? Science of the Total Environment, 684, 314–325.

Vasic, V., Djuric, S., Jafari-Hajnal, T., Orlovic, S., Vasic, S., Poljakovic Pajnik, L., Galović, V., 2019. The microbiological response of forest soils after application of nicosulfuron, imazamox and cycloxydim. International Journal of Environmental Science and Technology, 16(5), 2305–2312.

Vischetti, C., Casucci, C., Perucci, P., 2002. Relationship between changes of soil microbial biomass content and imazamox and benfluralin degradation. Biology and Fertility of Soils, 35(1), 13–17.

Wu, H., He, X., Dong, H., Zhou, Q., Zhang, Y., 2017. Impact of microorganisms, humidity, and temperature on the enantioselective degradation of imazethapyr in two soils. Chirality, 29(7), 348–357.

Zarzecka, K., Gugala, M., Grzywacz, K., Sikorska, A., 2020. Agricultural and economic effects of the use of biostimulants and herbicides in cultivation of the table potato cultivar Gawin. Acta Scientiarum Polonorum. Agricultura, 19(1), 3–10.

Determination of spatial distribution of key macro-nutrient contents in soils under different agricultural land uses

Sümeyya Ecem TONBUL ÇALOĞLU *, Orhan DENGİZ, Sena PACCİ
Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Sümeyya Ecem TONBUL ÇALOĞLU
ecemcaloglu@gmail.com

Abstract
This study was carried out in a 332.7-hectare experimental field belonging to Ondokuz Mayıs University, located in the Ladik district of Samsun province. The primary objective was to determine the spatial distribution of total nitrogen (N), available phosphorus (P), and available potassium (K) contents in soils under different land use types. For this purpose, soil samples were collected from 53 points at a depth of 0-15 cm. Fourteen different interpolation methods were compared to identify the most accurate technique for mapping the spatial distribution, and the method yielding the best results was used to create spatial distribution maps for N, P, and K. The results indicated that N content was relatively low in the northern and southern parts of the study area, whereas moderate to high levels were observed in the central regions. P content showed a higher concentration in the northern parts, which gradually decreased towards the southern areas, where it was found to be low. K content was found to be higher in the northeastern section of the study area, while the majority of the area exhibited low to moderate concentrations. These findings offer essential insights into soil fertility and provide a foundation for improved soil management and agricultural planning.

Keywords: Total nitrogen, available phosphorus, available potassium, interpolation

Introduction

Soil is one of the most valuable and non-renewable resources offered to us by nature. It is formed by complex processes lasting thousands of years and its biological, chemical and physical properties are constantly changing. This variability is greatly affected by natural factors as well as human soil management practices. Improperly managed soil not only destabilizes the ecosystem, but also puts human health and food security at risk in the long term (Nogueira et al., 2006). For sustainable agriculture, the balance of essential nutrients such as nitrogen, phosphorus and potassium in the soil is of great importance. These elements are essential for healthy plant growth and high yields. However, natural processes often do not ensure sufficient levels of these elements. For this reason, chemical fertilizers are widely used to restore the nutrients the soil needs. However, when this practice is uncontrolled and unconscious, it does more harm than good.

The spatial variability of soil fertility causes traditional statistical methods to be insufficient to reveal this variation (Başbozkurt et al., 2013). Classical methods assume that samples are statistically independent and ignore the spatial relationships of sample points. For this reason, geostatistical methods are preferred for the estimation of non-sampled points with the help of sampled points and the accuracy of these estimates. Geostatistics is a method that statistically and analytically evaluates the spatial correlation between samples and provides valuable information to researchers through interpolation and extrapolation techniques (Ersoy and Yünsel, 2008). Nowadays, GIS-based geostatistical methods are used to determine the spatial distribution of soil variable parameters and to make more comprehensive analyses on these parameters. The data are classified according to certain criteria, transferred to the computer environment and analysed by interpolation techniques and distribution maps are created. Thanks to these techniques, geographical data are spread over the whole area and the accuracy of spatial analyses is increased (Heuvelink, 2006). Many studies have been conducted on the application of these methods in Turkey and in the world (Arslan et al., 2012; Wang et al., 2014; Temizel, 2016).

Determination and monitoring of soil properties are of great importance in order to obtain high yields in agricultural activities. Understanding soil variability processes and spatial distribution of this variability is essential for effective and sustainable soil management. Ignoring changes in soil can lead to undesirable consequences (Behera and Shukla, 2015). Spatial variability can be caused by natural soil formation processes as well as human activities

Chemical and organic inputs used in agricultural production, removal of plant nutrients from the soil in various ways, pesticides and crops grown play an important role in the change of soil properties. In this study, the spatial distribution of total nitrogen (N), useful phosphorus (P) and useful potassium (K) contents of soils under different land uses was determined in an area of approximately 332 ha belonging to Ondokuz Mayıs University in Ladik district of Samsun province.

Material and Methods

Location, soil structure and climatic conditions of the study area

The study area was 332.7 da area located between the coordinates 734400-744000 East and 4535100-4535900 North (WGS 84, Zone 367, UTM-m) of Ondokuz Mayıs University in Ladik district of Samsun province (Figure 1).

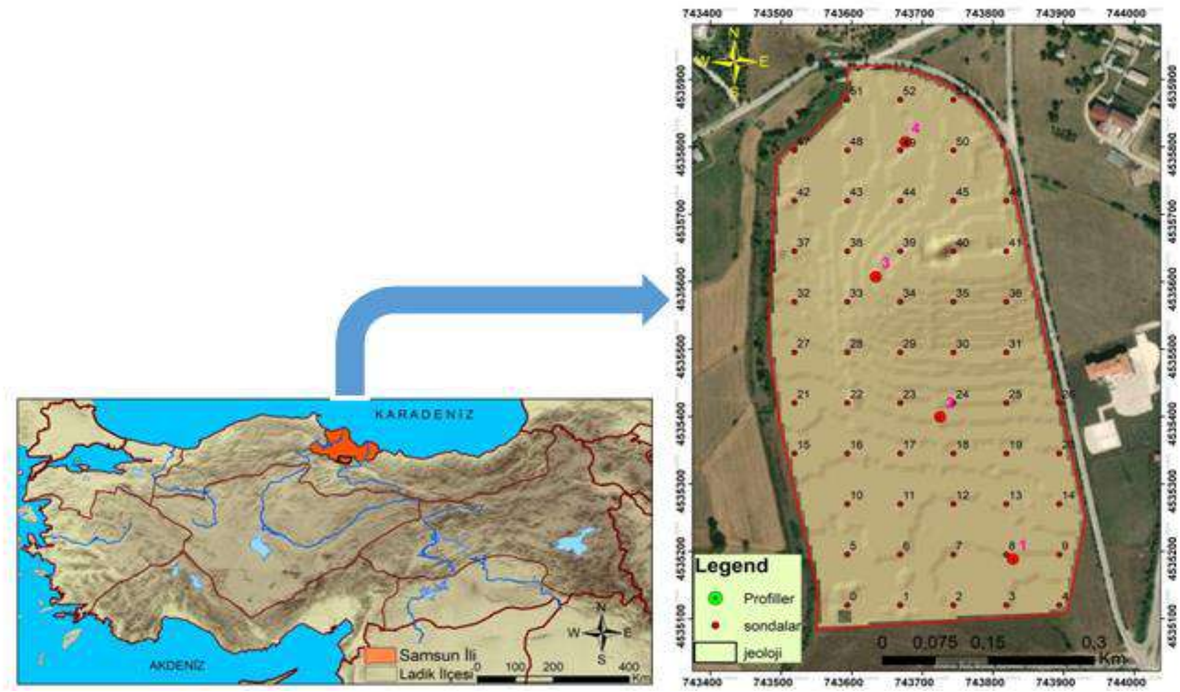


Figure 1. Location map of the study area

The study area is located between 899 m and 921 m above sea level. The majority of the area has mild to moderately steep slopes, and the moments distributed in the central parts are flat and nearly flat slopes. According to the meteorological measurements of Ladik district meteorological station for many years, the annual total precipitation and temperature values are 602 mm and 9.4 oC. In addition, soil moisture and temperature regimes were determined as Xeric and Mesic according to Newhall model.

Soil Samples and Analyses

A total of 53 soil samples were taken from the surface (0-20 cm) soils of the study area according to 200 m x 200 m grit system with the help of GPS (Figure 1). The soil samples were sieved through a 2 mm sieve and prepared for N, P and K analyses. Table 1 was used to determine the limit values of nutrient elements.

- Available Potassium (K): Determined by analyzing potassium extracted with 1 N ammonium acetate (NH4OAc) (U.S. Salinity Labrotory, 1992).
- Total nitrogen: Determined by Micro Kjeldahl method (Bremner and Mulvaney, 1982).
- Available Phosphorus (P): Determined using the Olsen method (Olsen, 1954).

Table 1. Limit values for N, P and K

Nutrient Elements	Values	Description
Total N (%)	<0.045	Very low
	0.045-0.09	Low
	0.09- 0.17	Moderate
	0.17-0.32	High
	> 0.32	Very high
P (mg kg^{-1})	<2.5	Very low
	2.5- 8.0	Low
	8.0- 25.0	Moderate
	25.0- 80.0	High
	> 80.0	Very high
K (mg kg^{-1})	<50	Very low
	50-140	Low
	140-370	Moderate
	370-1000	High
	>1000	Very high

Spatial distribution maps of total N, P and K contents of the soils of the study area were produced by determining the most appropriate model by using interpolation models to determine the spatial distribution of the point data obtained from soil analyses. Spatial distribution maps were prepared with ArcGIS 10.2.2 programme by using the analysis results of the soil samples taken from the sampling points whose coordinates were determined in the study area and the geographical data of the study area by using interpolation methods. In this study, Radial Basis Function (RBF) and Inverse Distance Weighted Interpolation (IDW) methods among deterministic methods and Ordinary Kriging (OK), Simple Kriging (SK) and Universal Kriging (UK) methods among stochastic methods were compared. In the study, first, second and third power (IDW-1, IDW2, IDW-3) models were used in IDW method, Completely Regularized Spline (CRS), Thin Plate Spline (TPS), and Spline With Tension (SWT) models in RBF method, and Spherical, Exponential and Gaussian models were used in kriging methods. In this study, the Root Mean Square Error Squared (RMSE) method was used to compare the methods in order to select the most appropriate methods. In model determination, the method with the lowest RMSE value was considered as the most appropriate method.

Results And Discussion

Descriptive statistics of total N, P and K analyses of soil samples taken from 0-20 cm depth in the study area were examined. When the descriptive statistics of the data obtained from the soil samples of the study area in Table 2 were analysed, it was determined that P showed a normal distribution according to the skewness coefficients, while total nitrogen (N) and K moved away from the normal distribution and exhibited log-normal distribution characteristics. Total nitrogen (N) varied between 0.03% and 0.18% and was determined at low level with an average of 0.08%. The content of useful phosphorus of soil samples ranged between 1.62 mg/kg and 4.09 mg/kg and was between low and very low classes. Useful potassium content of the soil samples was 282.2 mg/kg on average and ranged between 179 and 444 mg/kg. According to Wilding (1985), values with a coefficient of variability below 15% are categorised as low, those between 15-35% as medium and those above 35% as high variability. Accordingly, total N showed a high level of variability, K showed a moderate level of variability and P showed a low level of variability in the soil samples taken from the study area.

Table 2. Descriptive statistics results of soil samples in the study area

Descriptive Statistics	N (%)	P (mg kg^{-1})	K (mg kg^{-1})
Average	0.08	3.02	282.2
Standard Deviation	0.03	0.42	6.50
Coefficient of Variation	37.5	13.90	23.03
Variance	0.001	0.18	42.28
Minimum Value	0.03	1.62	179.0
Maximum Value	0.18	4.09	444.0
Skewness	0.79	-1.45	0.35
Kurtosis	2.20	4.30	-0.70

In order to determine the spatial distribution of the point data obtained from soil analyses, IDW, RBF, which are the most commonly used deterministic methods among the interpolation models, and Ordinary Kriging (OK), Simple Kriging (SK), Universal Kriging (UK) methods among the stochastic methods were used to compare the results and the method that gives the lowest Root Mean Square Error (RMSE) value was selected as the most appropriate method. When Table 3 is analysed; it is seen that the lowest RMSE values for total N and Pav values are obtained from the Exponential model for total N and Gaussian model for Pav in the UK method, and the best method for the most appropriate areal distribution of K values is the Exponential model in the UK method.

Table 3 RMSE values of the interpolation methods for the study area's soils

			N (%)	P (ppm)	K (ppm)
IDW		1	0,02594	0,44350	5,43948
		2	0,02577	0,46954	5,20016
		3	<u>0,02574</u>	0,49235	5,02870
RBF		CRS	0,02589	0,50868	<u>4,56057</u>
		SWT	0,02579	0,48810	4,58718
		TPS	0,02833	0,63096	4,68657
Kriging	Ordinary	Spherical	0,02682	0,45506	4,91153
		Exponential	0,02685	0,46220	4,75240
		Gaussian	0,02685	0,44336	4,88203
	Simple	Spherical	0,02590	<u>0,41767</u>	4,86449
		Exponential	0,02595	0,41791	4,79232
		Gaussian	0,02593	0,41749	4,79907
	Universal	Spherical	0,02606	0,45506	4,91153
		Exponential	0,02614	0,46220	4,75240
		Gaussian	0,02612	0,44336	4,88203

When Table 3 is analysed; it is seen that the lowest RMSE values for total N is IDW-3, and Spherical model of Simple Kriging for P values and the best method for the most appropriate areal distribution of K values is the CRS of model in the RBS method.

The source of soil nitrogen is soil organic matter or humus together with atmospheric nitrogen. 92-96 % of soil nitrogen is organic nitrogen. Nitrogen, one of the essential macronutrients that must be present in the soil for optimal growth and development of plants in agricultural production, significantly affects soil fertility depending on the selected soil management methods. In order to evaluate the variability of total nitrogen content in soils more precisely, especially in terms of nitrogen fertiliser management, the spatial distribution map of total nitrogen was examined in seven different class ranges (Figure 2). According to the total nitrogen distribution map, it was determined that the nitrogen contents of the soil samples were intensively distributed especially between 0.03-0.18%. The areas where total nitrogen is relatively less are generally distributed in the east and central parts of the research area, while the areas where it is too much are distributed in the north and south. In the areas where total nitrogen is sufficient and high, it was determined that intensive chemical fertiliser use and intensive tillage agriculture were carried out. The northern areas where nitrogen is low are shallow soils and there is not much agricultural activity.

Phosphorus is an indicator of soil fertility. It is a very important macronutrient element because it increases root development, maturation, fertilisation, early seed formation and resistance to diseases and pests. Since the fixation of phosphorus in the soil is high, its availability for the plant varies considerably according to the natural environment conditions and soil management practices. In 53 soil samples, P content varied between very low and low limit values with an average of 3.02 mg kg^{-1}. In order to examine the variability of P content trend of soils more precisely, their distribution in ten different class intervals was determined in the areal distribution maps (Figure 3). According to the distribution map, phosphorus content of the soils decreases in the southern parts of the area and increases towards the north. Maize is cultivated in the central areas where phosphorus is concentrated and wheat is cultivated in the northern areas.

The process of potassium retention in the soil or its transformation back into a form useful for plants has not yet been fully clarified. However, it is known that changes in soil reactions affect the dynamic structure of potassium in soil. The distribution of potassium in the soil varies due to the fact that some other soil properties such as the amount and type of clay, lime content, pH value of soils are effective on the processes such as the release or retention (fixation) of potassium in the soil. In order to examine the variability of the K content of soils more precisely, 10 different class intervals were determined in the spatial distribution maps (Figure 4).

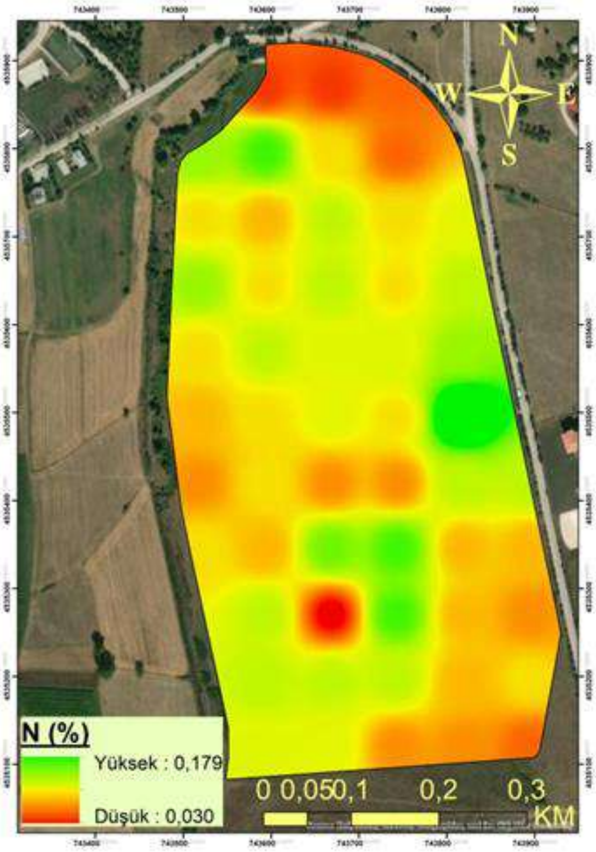


Figure 2. Distribution map of total nitrogen in the study area

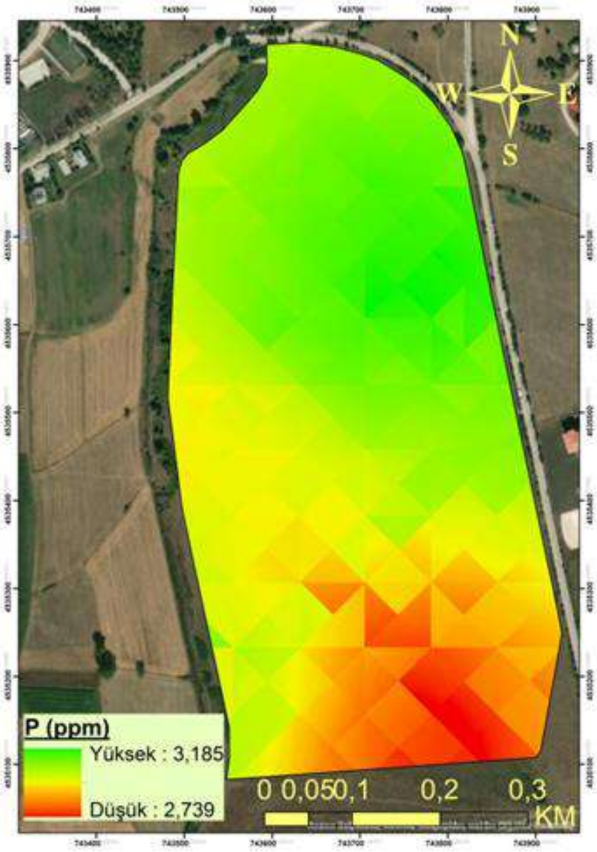


Figure 3. Distribution map of available phosphorus (P) in the study area.

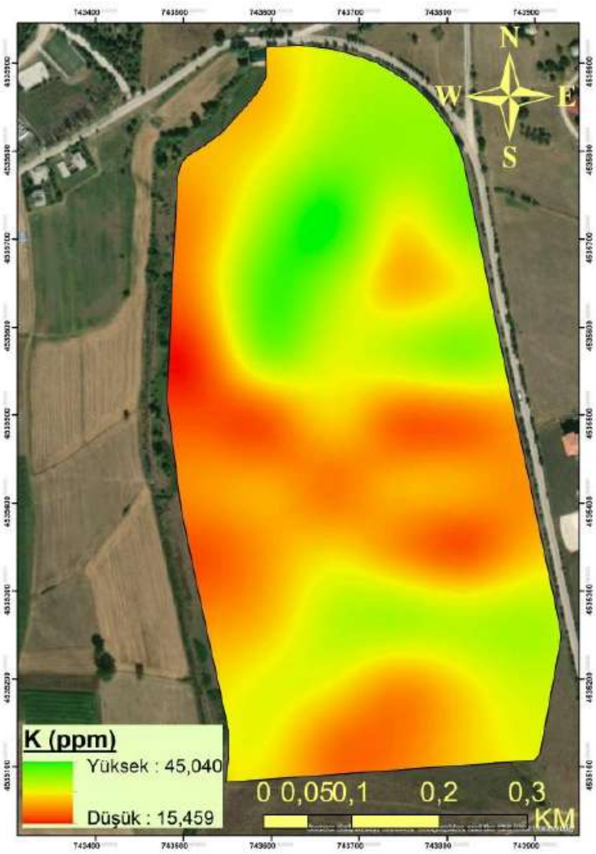


Figure 4. Distribution map of total potassium in the study area

According to the results of the analyses, the K contents of the soil samples are distributed between 179-444 mg kg^{-1} sufficient limit values in a small area in the southeast of the study area, whereas a significant portion of the soil samples are concentrated between in the north and northeast of the study area. Although the distribution of clays varies from place to place depending on the sediment deposit and soil, it is determined that the lowest values located in the central and west part of the study area.

Conclusion

In this study, the spatial distributions of the distance dependent relationships and changes of total N, P and K contents of soil samples taken from 53 different sampling points at surface soil depth (0-20 cm) in approximately 332 ha of irrigated and dry farming area were determined by the most appropriate interpolation method. Thus, the maps created by combining the parcel map showing the land use pattern with the parcel map showing the land use pattern in the geographical information system environment constituted an important source for revealing the positive or negative effects of the change and making suggestions such as what measures should be applied in the negatively affected areas. For this purpose, IDW, RBF, SK, UK and OK methods were tested. The lowest RMSE values for total N are IDW-3, and Spherical model of Simple Kriging for P values and the best method for the most appropriate areal distribution of K values is the CRS of model in the RBS method.

In order to obtain high- and high-quality products in agricultural production, it is very important that the plant nutrients needed by the plant are given to the soil in sufficient amounts and properly. In line with the evaluations made, it is seen that the nitrogen content of the soils in the study area is sufficient or high, although it is low in some sampling points. When the results obtained from the field identification studies and soil analyses are evaluated, it is understood that only a small part of the nitrogen source is from organic matter, and excessive nitrogen fertiliser (ammonium nitrate, ammonium sulphate, DAP, urea) applications are seen in the soils due to unconscious and excessive nitrogen fertiliser (ammonium nitrate, ammonium sulphate, DAP, urea) applications by farmers. While insufficient nitrogen in the soil affects plant growth negatively, excessive nitrogen contents also affect plant growth negatively. In addition, nitrogen losses through leaching from the soil can also cause environmental pollution by reaching water bodies such as groundwater, lakes and dams. Therefore, this situation may cause negative consequences both ecologically and economically.

In conclusion, the findings obtained in this study reveal that soil properties change with land use. Considering these changes and plant characteristics, fertiliser management planning in these areas will be one of the important elements of successful soil management.

Acknowledgments

This research was supported by Ondokuz Mayıs University under the project code BAP01-2024-5185. The authors thank all contributors for their valuable support.

References

Akyürek Ö, Arslan O, Karademir A (2013). SO2 ve PM10 hava kirliliği parametrelerinin CBS ile konumsal analizi: Kocaeli örneği, TMMOB Harita ve Kadastro Mühendisleri Odası Ulusal Coğrafi Bilgi Sistemleri Kongresi, 11-13 Kasım, Ankara.

Arslan H, Cemek B, Güler M, Yıldırım D (2012). Değişebilir sodyum yüzdesinin (ESP) konumsal dağılımının farklı enterpolasyon yöntemleri ile değerlendirilmesi. II. Ulusal Sulama ve Tarımsal Yapılar Sempozyumu, 24-25 Mayıs, İzmir.

Başbozkurt H, Öztaş T, Karaibrahimoğlu A, Gündoğan R, Genç A. (2013). Toprak özelliklerinin mekansal değişim desenlerinin jeoistatistiksel yöntemlerle belirlenmesi. Atatürk Üniversitesi Ziraat Fakültesi Dergisi, 44(2): 169-181.

Behera S K, Shukla A K (2015). Spatial distribution of surface soil acidity, electrical conductivity, soil organic carbon content and exchangeable potassium, calcium and magnesium in some cropped acid soils of India. Land Degradation Development, 26: 71–79

Bremner J M, Mulvaney C S (1982). Nitrogen-Total. In: Page, A.L., Miller, R.H., Keeney, D.R (Eds.), Methods of Soil Analysis, Part 2. Chemical and microbiological properties. 2 nd ed. Agronomy 9: 595-624.

Emadi M, Baghernejad M (2014). Comparison of spatial interpolation techniques for mapping soil pH and salinity in agricultural coastal areas, northern Iran. Archives of Agronomy and Soil Science, 60(9): 1315– 1327.

Ersoy A, Yünsel T Y (2008). Maden rezerv hesapları klasik ve jeoistatistik yöntemler. Nobel Kitabevi, Adana, s.103

Heuvelink G B M (2006). Incorporating process knowledge in spatial interpolation of environmental variables. Accuracy 2006 (7th International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences), pp. 32-47. 5-7 July, Lisbon, Portugal.

Olsen S R, Cole C V, Watanable F S, Dean L A (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939. U.S Government Printing Office, Washington D.C.

Combined effect of biochar and peat application on soil evaporation

Ayşe Asel FİDAN*, Salih DEMİRKAYA, Coşkun GÜLSER
Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Ayşe Asel FİDAN
aselfidan@gmail.com

Abstract

Sandy soils, with their coarse texture and low organic matter content, often struggle to retain water, making them less suitable for plant growth in arid and semi-arid conditions. Amending sandy soils with biochar and peat can significantly improve water retention. Biochar, with its porous structure and high surface area, increases the soil's ability to hold water in micropores, while improving infiltration and reducing water loss through drainage. Peat, on the other hand, is rich in organic matter and has a spongy structure that can absorb and retain large amounts of water. When used together, biochar and peat have a synergistic effect by increasing the soil's ability to hold water and slowly release it to plants. The objective of this study was to determine the effects of rice husk biochar (B) and peat (P) applications on total evaporation of a sandy loam soil. After the sandy loam soil sample was passed through 2mm size opening sieve, 1% ratio of rice husk biochar, peat and a combination of both materials (0.5% B+0.5%P) were incorporated to the soil sample in a completed randomized plot design with three replications. The pots including control, biochar, peat and BxP treatments were placed in an incubator at 25°C and kept around field capacity by weighing and irrigating with distillated water daily. Incubation experiment was done at the end of 30 days. Mean of the total amount of evaporation from treatments varied between 127,94 ml in control treatment and 138,86 ml in peat treatment. All treatments increased total evaporation over the control treatment. Increases in total evaporation according to the control treatment was 5,92% in B, 8,53% in P and 1,75% in BxP treatments. It was found that applications of B and P increased total evaporation in the sandy loam soil while increase of total evaporation in BxP treatment was less than B and P applications itself. It can be suggested that using a mixture of biochar and peat as a soil conditioner can help to water storage in coarse textural soils.

Keywords: Soil conditioner, Organic material, Soil moisture, Incubation

Introduction

The determination of soil evaporation is of great importance for several reasons, including the enhancement of agricultural productivity, the optimization of sustainable water resource management, and the improvement of environmental governance. Soil evaporation constitutes a component of evapotranspiration, which represents a significant proportion of plant water consumption and plays a critical role in plant growth, irrigation planning, and water conservation strategies (Allen et al., 1998; Lal, R., 2001; IPCC, 2021). Soil evaporation is also a critical process in agricultural systems, affecting water availability to crops and overall water use efficiency. Excessive soil evaporation can lead to significant water loss, reducing the amount of moisture available for plant uptake. To address this, researchers have investigated soil amendments such as biochar and peat, which are known to improve soil properties and reduce water loss.

Biochar is a carbon-rich material produced by the pyrolysis of organic biomass under anaerobic conditions. Its porous structure and high surface area contribute to improved soil water retention. For example, studies have shown that biochar can reduce evaporation by creating a physical barrier to water vapour diffusion and increasing the water-holding capacity of the soil (Abel et al., 2013). In addition, biochar has been observed to improve soil aggregation, which further limits water loss through evaporation (Lehmann & Joseph, 2015).

Peat, on the other hand, is an organic material formed from the partial decomposition of plant matter under waterlogged, low-oxygen conditions. It is rich in organic matter and has a high cation exchange capacity, which improves soil structure and its ability to retain water. Peat's role in reducing soil evaporation has been documented in several studies, highlighting its ability to act as a moisture-holding layer in soil systems (Zwarich et al., 1990).

Despite extensive research into the individual effects of biochar and peat, their combined application and synergistic effects on soil evaporation are relatively unexplored. Combining these amendments could exploit their complementary properties - biochar's ability to improve soil structure and peat's ability to retain moisture - to create a more effective water conservation strategy. Research suggests that such combinations could also influence soil microbial activity, nutrient cycling, and other soil properties, contributing to sustainable agricultural practices (Glaser et al., 2002; Cayuela et al., 2014).

In many studies, increasing total porosity by the organic amendment applications due to decreasing bulk density has been reported (Gülser and Candemir, 2015; Gülser et al. 2017; Demir and Gülser, 2021). Increasing macroporosity in bulk soil has an important effect on water retention (Mamedov et al. 2016). Understanding the interaction between biochar and peat in regulating soil evaporation is critical, particularly in regions facing water scarcity. The objective of this study was to determine the effects of rice husk biochar (B) and peat (P) applications on total evaporation of a sandy loam soil under controlled conditions.

Material and Methods

Sandy loam soil sample used in the study was taken from Ondokuz Mayıs University Agricultural Study Area, Bafra, Samsun. Then, the soil was air-dried and passed through a 2-mm sieve for analysis. The general characteristics of the soil sample used in the experiment are as follows: sand 75%, clay 17%, silt 8%, pH 7.60, EC 0.55 dS/m, organic matter 1.40%, and lime 13.4%. Soil pH and electrical conductivity were measured in a 1:1 soil:water mixture using a pH and EC meter. Soil texture was measured by hydrometer method (Gee and Or, 2002), organic matter content Walkley Black method (Nelson and Sommers 1982) and lime content was determined by calcimeter (Moodie et al., 1959).

The biochar material used in the study was produced from paddy husk at 350 ˚C in an oxygen-free environment in a muffle furnace. Peat material was purchased commercially.

For the incubation experiment, 150 g soil samples were mixed with biochar and peat at a dose of 1%, and in the combination of these treatments, a mixture dose of 0.5% biochar and 0.5% peat was used. The whole pots were placed in an incubator at 25°C and kept around field capacity by weighing and irrigating with distillated water daily. An incubation experiment was done at the end of 30 days. To determine the moisture loss due to evaporation, the amount of water lost per day was recorded.

Results and Discussion

In this study, the effects of biochar (B), derived from rice husks, and peat (P) applications on the total evaporation of a sandy loam soil were investigated under the controlled conditions. During the incubation experiment at field capacity moisture content and 25°C, the daily cumulative water losses of the treatments are presented in Figure 1. While no significant differences were observed in water losses among the treatments during the initial stages of the experiment, it was noted that the water losses among the treatments started to differ significantly, particularly after the 10th day.

The porous structure of biochar enables it to retain water. However, it should be noted that biochar and peat exhibit disparate water retention mechanisms, which may give rise to variations in total evaporation. Biochar retains water physically due to its high porosity, whereas peat absorbs water chemically as a result of its organic composition. The disparate water retention mechanisms result in the diversification of the effects of both materials on soil moisture dynamics and evaporation processes (Sağlam et al., 2009; Gomez et al., 2014).

At the end of the experiment, the total amount of water evaporated from the treatments was 127.94, 130.18, 135.52, and 138.86 ml for the control, biochar+peat, biochar, and peat treatments, respectively (Figure 2). Compared to the control, the highest evaporation occurred in the peat treatment, which was 8,53% higher (Figure 3). In the mixture of biochar and peat, evaporation was lower compared to when these treatments were applied separately. Lehmann and Joseph, (2015) reported that the high carbon content and water retention capacity of biochar improve the moisture balance of soils, while the peat provides organic matter that retains water for longer periods and facilitates plant access. They concluded that the combination of these two materials represents an effective solution to the low water retention capacity of sandy soils, while simultaneously reducing evaporation losses

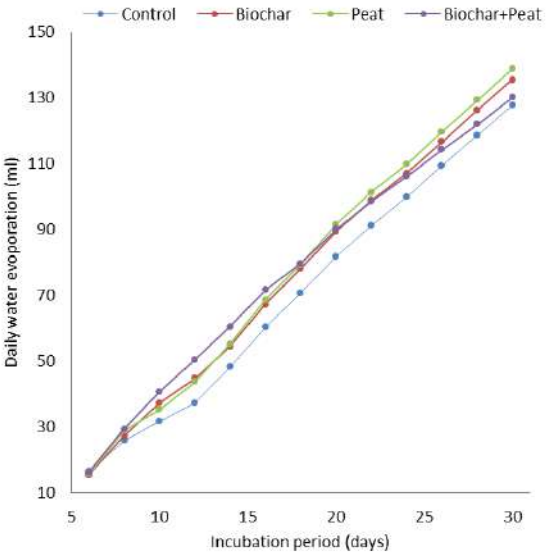


Figure 1. Daily cumulative water evaporation of the treatments during incubation

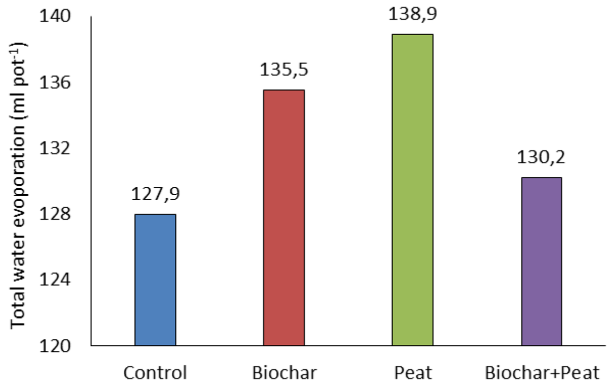


Figure 2. Total water evaporation of the treatments at the end of incubation

.

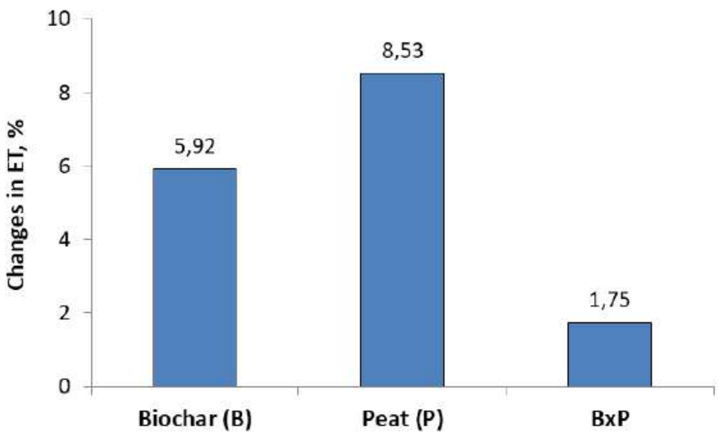


Figure 3. Increment percentages in total evaporation in the treatments over the control application.

One of the most noteworthy characteristics of peat is its capacity to absorb and retain significant quantities of water within its structure for extended periods (Özgümüş, 1985). Peat is capable of holding between 15 and 20 times its dry weight in water, which results in prolonged and increased water retention in the soil, consequently leading to higher evaporation. It has been demonstrated that peat enhances water retention, particularly in arid and sandy soils, thereby creating an optimal environment for plant growth (Michel, 2010; Holden et al., 2011; Okruszko and van der Ploeg, 2012). Peat not only mitigates the effects of drought by facilitating the gradual release of water, but it also maintains an optimal moisture balance for plant roots. Consequently, there is a growing interest in utilising peats for the regulation of soil moisture in agricultural practices.

Conclusion

The regulation of evaporation in coarse texture soils is of particular importance for the efficient utilization of water and the optimization of plant growth. In this context, the use of organic materials, such as biochar and peat, has been a subject of considerable interest. The results of the incubation experiment in this study demonstrated the influence of biochar and peat applications, both individually and in combination, on soil evaporation dynamics. While no significant differences in water loss between treatments were observed in the early stages, significant differences were observed after day 10. Interestingly, the combination of biochar and peat resulted in a reduction in evaporation compared to their individual applications, suggesting a synergistic effect when these amendments are used together. Future research should investigate the long-term effects and scalability of these treatments to optimise their application in agricultural practice.

References

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., Wessolek, G., 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma, 202–203*, 183–191. doi:10.1016/j.geoderma.2013.03.003

Allen, R. G., Pereira, L. S., Raes, D., Smith, M., 1998. *Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56.* Food and Agriculture Organization of the United Nations, Rome.

Cayuela, M. L., van Zwieten, L., Singh, B. P., Jeffery, S., Roig, A., Sánchez-Monedero, M.A., 2014. Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agriculture, Ecosystems & Environment, 191*, 5–16. doi:10.1016/j.agee.2013.10.009

Demir, Z. and Gülser, C., 2021. Effects of Rice Husk Compost on Some Soil Properties, Water Use Efficiency and Tomato (Solanum lycopersicum L.) Yield under Greenhouse and Field Conditions. Communications in Soil Science and Plant Analysis, pp.1-18.

Demirkaya, S., Öztürk, E., 2022. Buğdayda verim ve verim parametrelerine toprak özelliklerinin etkisi. *Toprak Bilimi ve Bitki Besleme Dergisi*, *10*(2), 159-164.

Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – A review. *Biology and Fertility of Soils, 35*(4), 219–230. doi:10.1007/s00374-002-0466-4

Gomez, J.D., Denef, K., Stewart, C.E., Zheng, J., Cotrufo, M.F., 2014. Biochar addition rate influences soil microbial abundance and activity in temperate soils. *European Journal of Soil Science*, 65(1), 28-39

Gülser C., Candemir F., 2015. Effects of agricultural wastes on the hydraulic properties of a loamy sand cropland in Turkey. Soil Science & Plant Nutrition 61 (3): 384-391.

Gülser C., Minkina T., Sushkova S., Kızılkaya R., 2017. Changes of soil hydraulic properties during the decomposition of organic waste in a coarse textured soil. Journal of Geochemical Exploration, 174, SI(1):66-69.

Günal, E., Erdem, H., 2018. Biyoçarın Toprağın Fiziksel, Kimyasal ve Biyolojik Özelliklerine Etkileri. *21. Yüzyılda Fen ve Teknik*, *2*(10), 29-58.

Holden, J., Evans, M.G., Burt, T.P., Horton, M., 2011. Impact of peatland drainage on runoff characteristics: A critical review. *Hydrological Processes, 25*(21), 3511-3534.

IPCC (2021). Climate Change 2021: The Physical Science Basis.

Kadıoğlu, B., 2014. *Pomza perlit ve torf karıştırılan toprak ortamların hidrofiziksel özellikleri ve bitki gelişimi üzerine etkileri* (Doctoral dissertation, Doktora Tezi, Atatürk Üniversitesi, Erzurum).

Lal, R., 2001. Soil degradation by erosion. *Land Degradation & Development*, 12(6), 519-539.

Lehmann, J., Joseph, S., 2015. *Biochar for Environmental Management: Science, Technology and Implementation*. Routledge.

Mamedov, A., Ekberli, I., Gülser, C., Gümüş, I., Çetin, U. and Levy, G.J.G., 2016. Relationship between soil water retention model parameters and structure stability. Eurasian Journal of Soil Science, 5(4), pp.314-321.

Michel, J.C., 2010. The role of peat in horticultural growing media. *Acta Horticulturae, 882*, 25-31.

Okruszko, H., van der Ploeg, R.R., 2012. Peatlands as a sustainable water resource. *Catena, 48*(1-2), 3-21.

Zwarich, M. A., De Jong, R., Read, D.W.L., 1990. The effects of peat and soil amendments on soil moisture retention and crop yields. *Canadian Journal of Soil Science, 70*(3), 545–556.

Comparative analysis of multiple linear regression and random forest regression for predicting soil salinity in paddy fields

Nursaç Serda KAYA*, Orhan DENGİZ
Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Nursaç Serda KAYA
nursackaya@gmail.com

Abstract
Soil salinity presents a major challenge to agricultural productivity and land quality, especially in irrigated regions. Remote sensing techniques, coupled with machine learning, offer efficient, accurate, and cost-effective solutions for monitoring and managing soil salinity. This study aimed to predict soil salinity in paddy fields of the Yeşil Küre Agricultural Enterprise by integrating remote sensing data with ground-based EC measurements using multiple linear regression (MLR) and random forest regression (RFR) models. Results indicated that the RFR model significantly outperformed the MLR model (R^2 = 0.97), demonstrating its ability to accurately capture non-linear relationships between soil salinity indices and EC values. Additionally, NDVI values were analyzed to assess vegetation health and its relationship with soil salinity, providing further insights into the dynamics of soil-vegetation interactions. These findings highlight the effectiveness of combining machine learning algorithms with remote sensing data for precise and efficient monitoring of soil salinity.
Keywords: Soil salinity, paddy fields, multiple linear regression, random forest regression, remote sensing

Introduction

Soil is a fundamental resource that supports essential ecosystem functions, particularly in agriculture. It also provides critical services such as water filtration, carbon dioxide regulation, and sustaining plant and animal biodiversity (Wilson, 2019). However, soil salinity has emerged as a significant concern. This issue, resulting from both natural processes and human activities, poses a significant threat to these functions, particularly in arid and semi-arid regions, by reducing crop yields and jeopardizing sustainability (Chang et al., 2019; Hailu and Mehari, 2021).

Identifying saline soils promptly and accurately is vital for preserving soil health and ensuring food security. Early detection and mapping of salinity are key to developing effective management and restoration strategies. While traditional ground-based methods have been widely used, advancements in satellite technology now enable more efficient monitoring and mapping of soil salinity, offering extensive, repeated observations with moderate to high accuracy (Allbed and Kumar, 2013). In recent years, soil salinity indices from satellite spectral bands have become a key method for mapping saline soils (Morgan et al., 2018). However, surface reflectance is influenced by properties like color, texture, and moisture, making it difficult for a single index to predict salinity accurately (Daliakopoulos et al., 2016). Researchers often use multiple indices, selecting those most correlated with ground data to improve model accuracy (Allbed and Kumar, 2013). Remote sensing provides high-resolution, regularly updated data, with sensors like Landsat-8 OLI, MODIS, and Sentinel-2 MSI assisting in salinity prediction since the 1990s (Golestani et al., 2023).

In recent years, machine learning techniques have demonstrated remarkable success in accurately mapping soil salinity across diverse geographical regions. These methods are highly effective in ecological modeling, utilizing multivariate calibration in combination with clustering and classification of remote sensing imagery (Vågen et al., 2013). When integrated with multispectral data, these algorithms significantly enhance the precision of saline soil classification. This study aims to predict soil salinity for the paddy fields within the lands of Yeşil Küre Agricultural Enterprise by integrating remote sensing data with ground-based EC measurements, utilizing multiple linear regression and random forest regression models. Additionally, NDVI values are analyzed to assess vegetation health and its relationship with soil salinity.

Material and Methods

Description of the study area

Yeşil Küre Agricultural Enterprise are located along the Samsun-Bafra highway at the 40th km, within the coordinates 249000-254000 East and 4599200-4602400 North (WGS84, Zone 37, UTM-m).

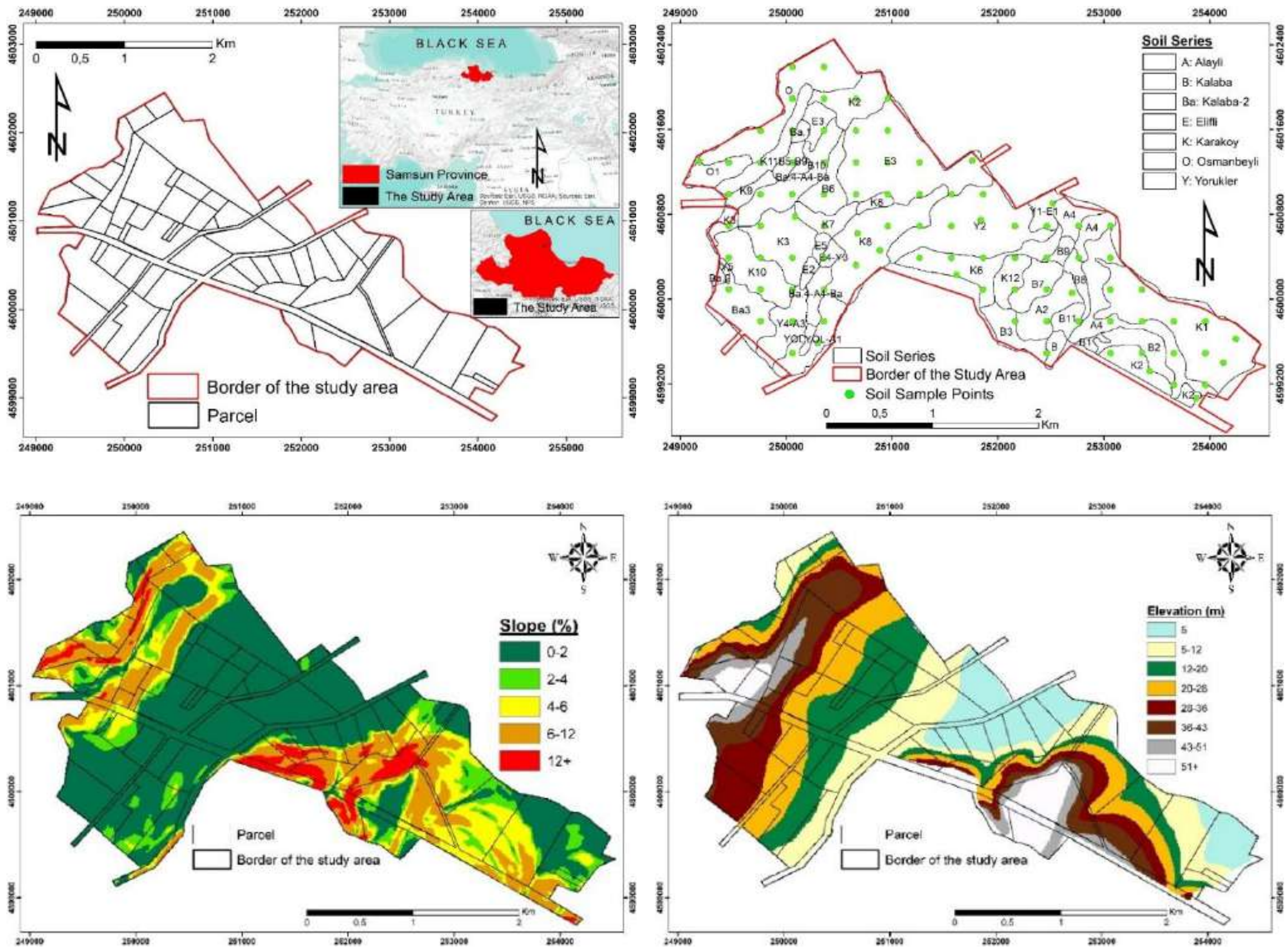


Figure 1. Maps of location, surface soil samples, slope, and elevation of the study area

The enterprise consists of two sections: Hara and Duden. The study area, Hara, covers 2336.7 hectares, but when the Duden area is included, the total expands to 9239.8 hectares. Hara is bordered by Duden to the east, the Black Sea to the north, Bunyan Mountain to the south, and the Bafra Plain to the west. Duden is situated along the western shore of Balık Lake within the Kızılırmak Delta. The location map of the study area is shown in Figure 1. The farmland is 5 to 74 meters above sea level. The northwest and southeast areas have moderately steep to steep slopes, while the central and northwestern parts are mostly flat or gently sloping, with gradients between 0% and 4% (Figure 1). The central Hara area of the study region has high levels of agricultural activity, with extensive cultivation of crops such as maize silage, wheat, alfalfa, and garlic, as well as the planting of hazelnuts and blackberries.

Soil Sampling and Analysis

In the study area, soil samples were collected by dividing the land into 300 m × 300 m grid squares, with a total of 89 sampling points. Samples were taken from a depth of 0–20 cm, representing various soil series (Figure 1). The collected samples were dried, sieved, and stored for further analysis. Details of the EC measurement protocol used in the study are provided in Table 1.

Table 1. Soil EC measurement protocol

Unit	Protocol	Reference
dS/m	(w:v) soil-water suspension	Soil Survey Staff, (1996)

Satellite Data and Preprocessing

A Sentinel-2A image from the Copernicus Open Access Hub (https://scihub.copernicus.eu/) was used in this study. The image provides spatial resolutions of 10 meters (4 bands), 20 meters (6 bands), and 60 meters (3 bands). Over the years, several spectral indices have been developed to map soil salinity, with many studies confirming their usefulness (Khajehzadeh et al., 2022; Golestani et al., 2023). While no single index is universally accepted for soil salinity, this study used nine commonly applied indices (Avdan et al., 2022). These indices, calculated from visible and near-infrared bands, were processed using ArcGIS 10.7v software. The indices are listed in Table 2.

Table 2. Spectral indices derived from the spectral reflectance of various bands

Salinity Index (SI)	Expression	References
SI_1	$SI_1 = \sqrt{B \times R}$	(Khan et al., 2005)
SI_2	$SI_2 = \sqrt{G \times R}$	(Khan et al., 2005)
SI_3	$SI_3 = \sqrt{G^2 \times R^2 \times NIR^2}$	(Nicolas and Walter, 2006)
SI_4	$SI_4 = \sqrt{G^2 \times R^2}$	(Nicolas and Walter, 2006)
SI_5	$SI_5 = \frac{B}{R}$	(Bannari et al., 2008)
SI_6	$SI_6 = \frac{B - R}{B + R}$	(Bannari et al., 2008)
SI_7	$SI_7 = \frac{G \times R}{B}$	(Bannari et al., 2008)
SI_8	$SI_8 = \frac{B \times R}{G}$	(Abbas and Khan, 2007)
SI_9	$SI_9 = \frac{NIR \times R}{G}$	(Abbas and Khan, 2007)

B: Blue, R: Red, NIR: Near-Infrared, G: Green.

Multiple Linear Regression

Linear regression is a statistical method used to predict values based on independent variables, aiming to identify relationships between them. The MLR model, widely used in soil science for its simplicity and ease of interpretation (Zhang et al. 2017). This study applies 10-fold cross-validation to improve the accuracy of the MLR model and to reduce the risk of overfitting (Kaya and Dengiz, 2024). The MLR model in this study was trained and tested with a testing size of 0.2, using Python 3.8, Anaconda3, and Spyder 5.2.2. Python was selected for its high accuracy and performance. The model used for the MLR is (Eq. 1):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots \beta_i x_i \tag{1}$$

where y is the dependent variable, β_0 is the regression constant, β_i is the coefficient of the independent variable, and x_i is the independent variable.

Random Forest Regression

RFR uses multiple decision trees to provide reliable and precise predictions. It efficiently processes numerical and categorical data, deals with missing values, and minimizes overfitting. Its versatility makes it suitable for tasks such as stock forecasting, customer retention analysis, medical diagnosis, and research. 10-fold cross-validation was also applied to the RFR model to improve its accuracy and minimize the risk of overfitting (Kaya and Dengiz, 2024). The RFR model in this study was trained and tested with a testing size of 0.2, using Python 3.8, Anaconda3, and Spyder 5.2.2. Python was selected for its high accuracy and performance. The default value of `n_estimators` in the RFR model is 10, but we set it to 100 to improve the model's accuracy. All other hyperparameters were kept at their default values.

Model Validation

Prediction involves two main steps: data preparation and model evaluation. This study assessed the performance of algorithms used for predicting soil salinity, focusing on the key metric, R^2. As a widely accepted indicator, R^2 is commonly used to evaluate the effectiveness of artificial neural networks and machine learning models (Kaya and Dengiz, 2024). A higher R^2 value signifies better performance of the regression model.

$$R^2 = \frac{\sum_{i=1}^{n}(P_i - \overline{O_i})^2}{\sum_{i=1}^{n}(O_i - \overline{O_i})^2} \tag{2}$$

where P_i and O_i are the estimated and observed values at site i, respectively; O̅_i is the mean observed value and n is the number of samples.

Results and Discussion

In this study, EC was utilized as the target variable, and salinity indices were used as independent variables in both machine learning models. The obtained R^2 values demonstrate that the RFR model outperformed the MLR model (Figure 4). This outcome can be attributed to the non-linear relationship between salinity indices and EC values (Figure 5). The RFR model performs at capturing complex non-linear interactions between input and output variables (Tajik et al., 2020), particularly when input variables exhibit high correlations (Kaya and Dengiz, 2024). In contrast, the MLR model is constrained to linear structures (Zhang et al., 2017; Moreover, Biau and Scornet (2016) emphasized RF's capability to construct decision tree ensembles, enhancing its effectiveness in modeling non-linear data. Similarly, Liu et al. (2021) demonstrated that RF generally achieves higher accuracy than MLR in scenarios where non-linear relationships predominate.

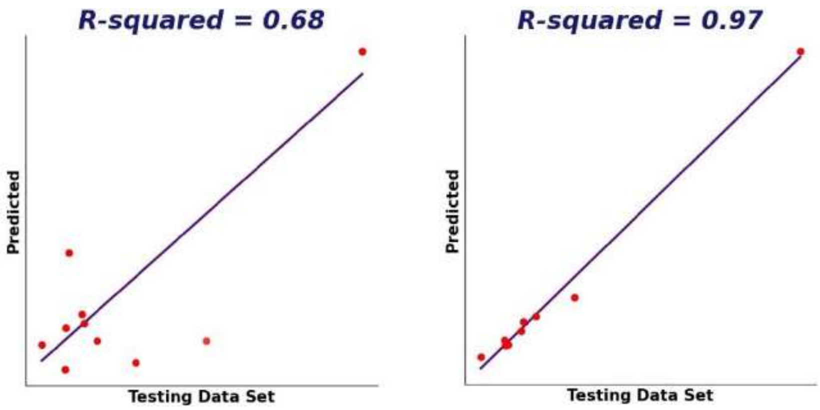


Figure 4. The comparison of testing and predicted data sets by MLR (left) and RFR (right) models

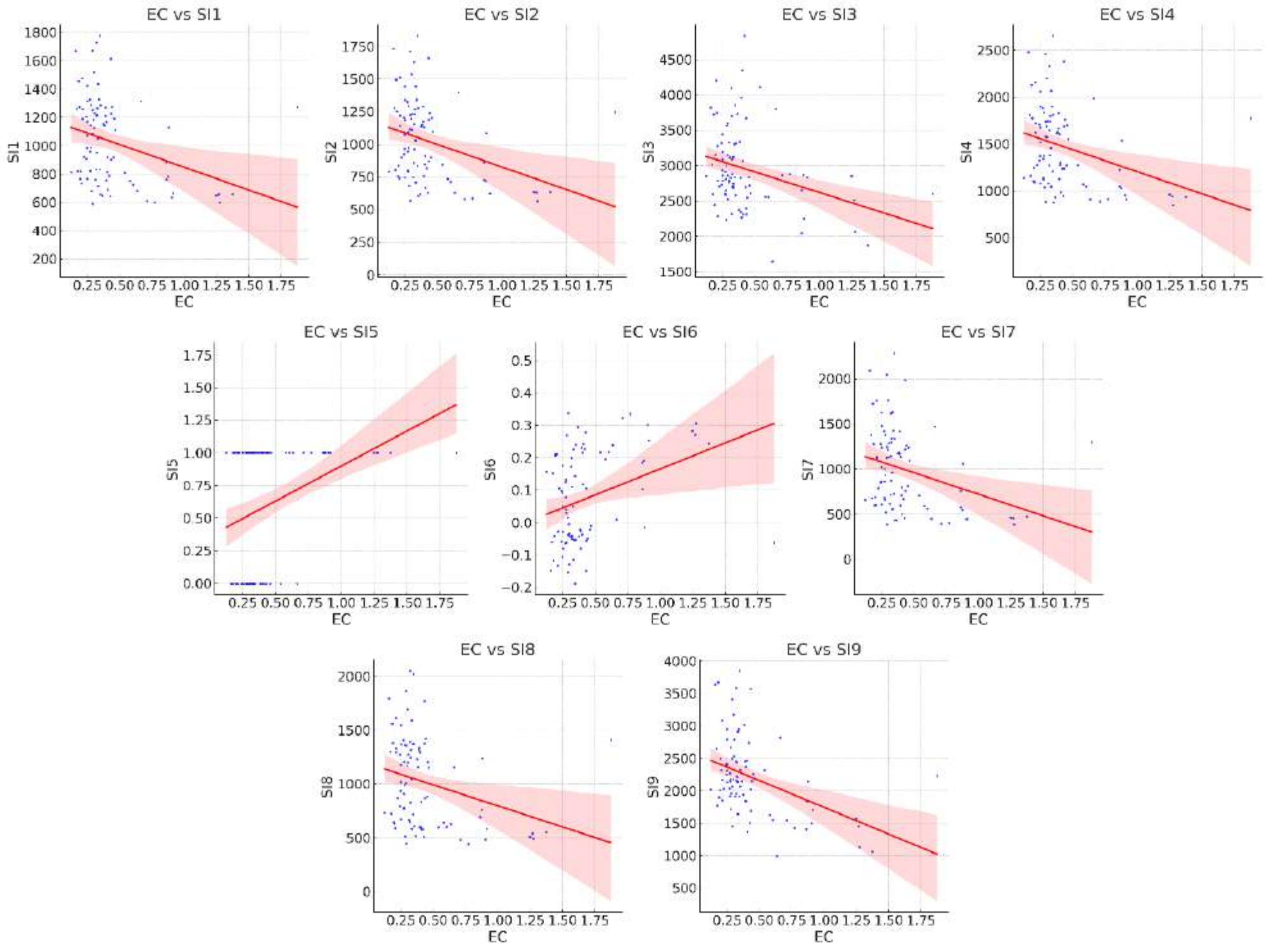


Figure 5. Relationship between soil EC and salinity indices

Figure 6 presents the distribution maps of EC in paddy fields for observed data, MLR, and RFR models. The creation of these maps involved the use of 15 different interpolation models utilizing ArcGIS 10.7v software (Kaya and Dengiz, 2024). Root Mean Square Error (RMSE) was employed to evaluate and identify the best-fitting interpolation model. The interpolation models with the lowest RMSE values were then used to generate the spatial distribution maps of EC (Kaya and Dengiz, 2024).

In this study, alongside salinity indices, NDVI values were also calculated, ranging from 0.12 to 0.77 (Figure 6). NDVI serves as an indicator of vegetation health, providing quantitative insights into the condition of diverse plant types through remote sensing data. The degree of plant greenness and overall crop health is intrinsically linked to soil salinity levels (Djuraev et al. 2021). A Sentinel-2A satellite image from July was utilized for the calculation of both salinity indices and NDVI values. This period corresponds to a critical phase in the growth cycle of rice plants when they reach their peak vegetation density. Following germination in May and June, rice plants exhibit the highest NDVI values during July and August. This peak is attributed to the dense canopy structure and shading effect of rice plants, which minimize soil reflectance and enhance NDVI values (Dengiz et al., 2022).

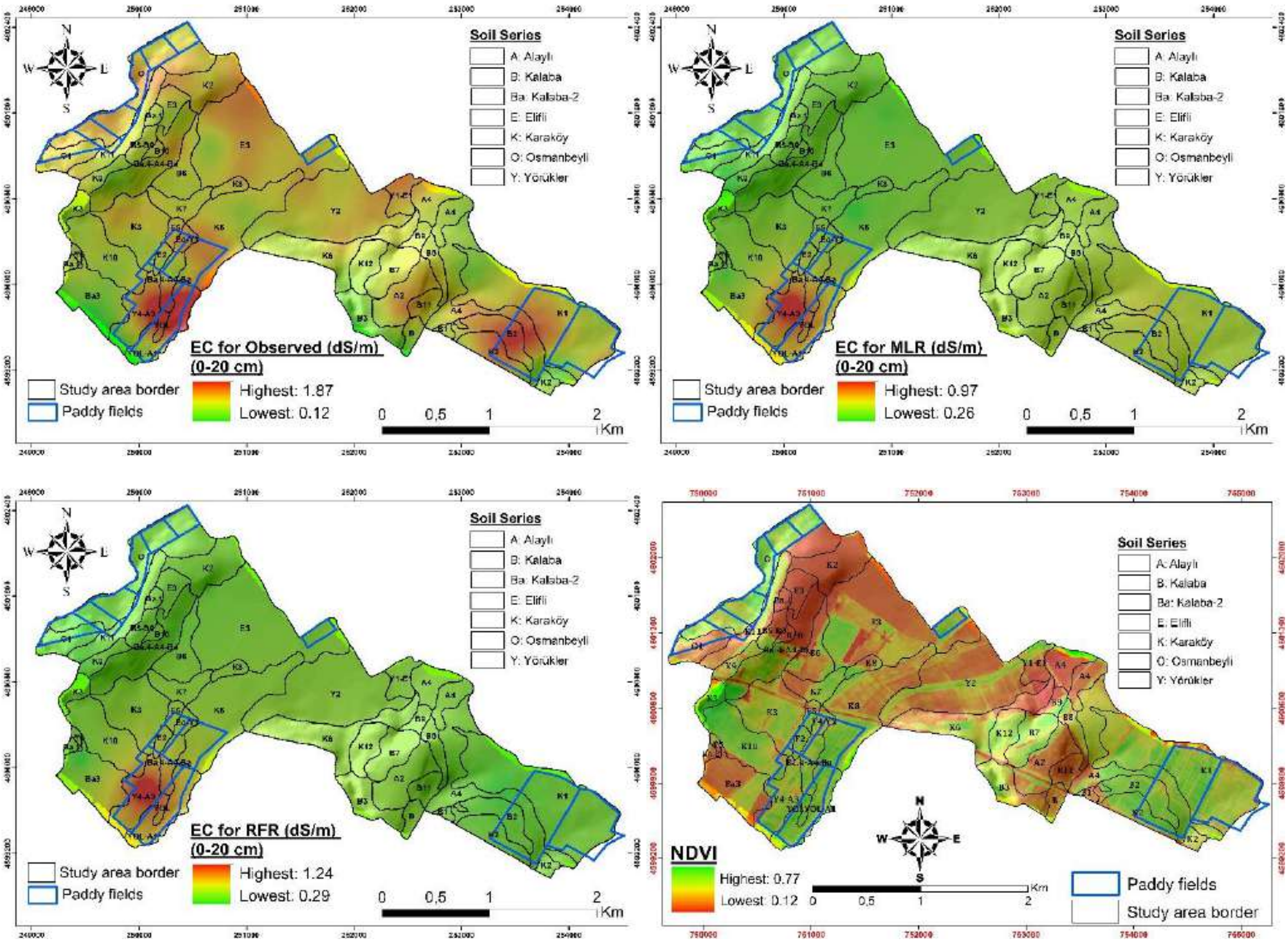


Figure 6. Distribution maps of soil EC in paddy fields for Observed data, MLR and RFR models, and NDVI values

The study area predominantly consists of non-saline soils (0–2 dS/m), which explains why NDVI values remained consistently high and stable. As shown in Figure 7, the scatter plot of NDVI and EC values clearly indicates that most of the study area falls within the non-saline soil category, where EC levels do not exert significant stress on plant health. This lack of salinity stress allows NDVI values to remain stable and high, emphasizing the reliability of vegetation indices in accurately representing healthy vegetation in areas with minimal soil salinity.

In conclusion, the findings of this study demonstrate that NDVI is not only an effective tool for evaluating vegetation health but also a critical metric for analyzing the interactions between soil salinity and plant health. The minimal salinity effects observed in the study area further highlight NDVI's ability to adapt to environmental conditions and reliably capture variations in vegetation density. These findings underscore NDVI's potential as a key indicator in understanding soil-vegetation dynamics in non-saline environments.

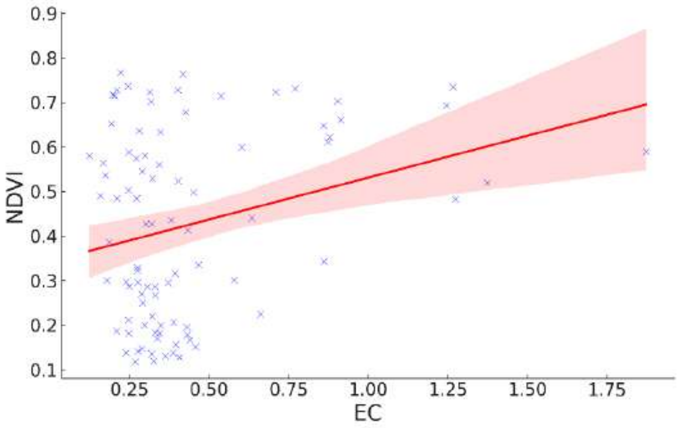


Figure 7. Relationship between NDVI and soil EC

Conclusion

Monitoring soil salinity is vital for global food security due to its detrimental impact on agricultural productivity. This study demonstrated that the RFR model significantly outperformed the MLR model, achieving superior accuracy in predicting soil salinity by effectively capturing non-linear relationships. In contrast, the MLR model showed limited predictive capability due to its reliance on linear structures. Additionally, NDVI values provided valuable insights into vegetation health and its relationship with salinity, further enhancing the analysis. These results highlight the potential of integrating machine learning and remote sensing for precise and efficient salinity monitoring. In future studies, model performance could be further enhanced by incorporating different vegetation indices and salinity indices combined with various bands, as well as including more topographic and soil properties to achieve more successful results.

References

Abbas, A., & Khan, S. (2007). Using remote sensing techniques for appraisal of irrigated soil salinity. In International Congress on Modelling and Simulation (MODSIM) (pp. 2632-2638). Modelling and Simulation Society of Australia and New Zealand.

Allbed, A., & Kumar, L. (2013). Soil salinity mapping and monitoring in arid and semi-arid regions using remote sensing technology: a review. Advances in remote sensing, 2013.

Avdan, U., Kaplan, G., Matcı, D. K., Avdan, Z. Y., Erdem, F., Mızık, E. T., & Demirtaş, İ. (2022). Soil salinity prediction models constructed by different remote sensors. Physics and Chemistry of the Earth, Parts A/B/C, 128, 103230.

Bannari, A., Guedon, A. M., El-Harti, A., Cherkaoui, F. Z., & El-Ghmari, A. (2008). Characterization of slightly and moderately saline and sodic soils in irrigated agricultural land using simulated data of advanced land imaging (EO-1) sensor. Communications in soil science and plant analysis, 39(19-20), 2795-2811.

Biau, G., Scornet, E. A random forest guided tour. TEST 25, 197–227 (2016).

Chang, X., Gao, Z., Wang, S., & Chen, H. (2019). Modelling long-term soil salinity dynamics using SaltMod in Hetao Irrigation District, China. Computers and Electronics in Agriculture, 156, 447-458.

Daliakopoulos, I. N., Tsanis, I. K., Koutroulis, A., Kourgialas, N. N., Varouchakis, A. E., Karatzas, G. P., & Ritsema, C. J. (2016). The threat of soil salinity: A European scale review. Science of the total environment, 573, 727-739.

Dengiz, O., Dedeoğlu, M., & Kaya, N. S. (2022). Determination of the relationship between rice suitability classes and satellite images with different time series for Yeşil Küre farm lands. Yuzuncu Yıl University Journal of Agricultural Sciences, 32(3), 507-526.

Djuraev, A., Mirdjalalov, D., Nuratdinov, A., Khushvaktov, T., & Karimov, Y. (2021). Evaluation of soil salinity level through NDVI in Syrdarya province, Uzbekistan. In E3S Web of Conferences (Vol. 258, p. 03017). EDP Sciences.

Golestani, M., Ghahfarokhi, Z. M., Esfandiarpour-Boroujeni, I., & Shirani, H. (2023). Evaluating the spatiotemporal variations of soil salinity in Sirjan Playa, Iran using Sentinel-2A and Landsat-8 OLI imagery. Catena, 231, 107375.

Hailu, B., & Mehari, H. (2021). Impacts of soil salinity/sodicity on soil-water relations and plant growth in dry land areas: A review. J. Nat. Sci. Res, 12, 1-10.

Kaya, N. S., & Dengiz, O. (2024). Assessment of the neutrosophic Fuzzy-AHP and predictive power of some machine learning approaches for maize silage soil quality. Computers and Electronics in Agriculture, 226, 109446.

Khajehzadeh, M., Afzali, S. F., Honarbakhsh, A., & Ingram, B. (2022). Remote sensing and GIS-based modeling for predicting soil salinity at the watershed scale in a semi-arid region of southern Iran. Arabian Journal of Geosciences, 15(5), 423.

Khan, N. M., Rastoskuev, V. V., Sato, Y., & Shiozawa, S. (2005). Assessment of hydrosaline land degradation by using a simple approach of remote sensing indicators. Agricultural Water Management, 77(1-3), 96-109.

Liu, M., Hu, S., Ge, Y., Heuvelink, G. B., Ren, Z., & Huang, X. (2021). Using multiple linear regression and random forests to identify spatial poverty determinants in rural China. Spatial Statistics, 42, 100461.

Morgan, R. S., El-Hady, M. A., & Rahim, I. S. (2018). Soil salinity mapping utilizing sentinel-2 and neural networks. Indian Journal of Agricultural Research, 52(5), 524-529.

Nicolas, H., & Walter, C. (2006). Detecting salinity hazards within a semiarid context by means of combining soil and remote-sensing data. Geoderma, 134(1-2), 217-230.

Tajik, S., Ayoubi, S., & Lorenz, N. (2020). Soil microbial communities affected by vegetation, topography and soil properties in a forest ecosystem. Applied Soil Ecology, 149, 103514.

Vågen, T. G., Winowiecki, L. A., Abegaz, A., & Hadgu, K. M. (2013). Landsat-based approaches for mapping of land degradation prevalence and soil functional properties in Ethiopia. Remote Sensing of Environment, 134, 266-275.

Wilson, M. J. (2019). The importance of parent material in soil classification: A review in a historical context. Catena, 182, 104131.

Zhang, H., Wu, P., Yin, A., Yang, X., Zhang, M., & Gao, C. (2017). Prediction of soil organic carbon in an intensively managed reclamation zone of eastern China: A comparison of multiple linear regressions and the random forest model. Science of the Total Environment, 592, 704-713.

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

Paulownia as a promising technical crop for biomass production

Lesia KARPUK*, Viktor TITARENKO, Oksana TITARENKO
Bila Tserkva National Agrarian University, Faculty of Agro-biothechnology, Department of Farming, Agricultural Chemistry and Soil Science, BilaTserkva, Ukraine, 09119

***Corresponding Author**

Lesia KARPUK
lesia.karpuk@btsau.edu.ua

Abstract
Paulownia is one of the most promising technical crops for industrial plantations due to its ability to rapidly accumulate biomass and adapt to diverse climatic conditions. This tree can be cultivated on both fertile soils and degraded or marginal lands, making it particularly valuable in regions with limited land resources. Studies confirm that the application of organic fertilizers, cryoprotectants, and foliar feeding significantly enhances the growth and productivity of Paulownia. By the third year of cultivation, the average stem diameter reached 17.3–18.4 cm, resulting in dry matter yields of up to 18.4 t/ha. This significantly surpasses the productivity of traditional energy crops. Biomass quality analysis revealed a high cellulose content (up to 44.5%) and lignin (20.7%), making Paulownia an ideal raw material for bioenergy production, paper manufacturing, plywood, and other industrial products. Paulownia also exhibits high resilience to stressful conditions, including low temperatures, due to the use of cryoprotectants. The combined application of organic fertilizers, foliar feeding, and growth regulators ensures optimal growth conditions and maximum biomass accumulation. The findings indicate that Paulownia can become a key component in the transition to sustainable agriculture, reducing dependency on fossil fuels and contributing to ecological balance preservation. The economic benefits of cultivating Paulownia include high investment returns, the versatility of its wood for numerous commercial applications, and its positive impact on local ecosystems. In Ukraine, Paulownia has significant potential as a crop with high energy and material yields per unit area, particularly in the context of climate change and increasing demand for renewable resources.

Keywords: Paulownia, biomass, technical crop, organic fertilizer, cryoprotectants, sustainable development, agrotechnical measures, energy crops

Introduction

Paulownia is quite an interesting and promising culture in the technical direction of processing. Low-quality wood can be obtained from 6-7-year-old trees, but to obtain higher-quality products, it is recommended to increase the cultivation time of plantations up to 10 years, and not to cut them at a young age. A fully formed paulownia tree can reach a height of 10 to 20 meters and have height gains of up to 3 meters per year under ideal conditions. A ten-year-old tree can have a diameter of 30-40 cm at breast height and a wood volume of 0.3-0.5 m^3 (Abreu et al., 2020; Candan et al., 2021).

Each paulownia tree can provide a cubic meter of wood at the age of 5-7 years, in addition, it can grow in intensive plantations with a density of up to 2000 trees per hectare. Based on this, it is possible to calculate that the annual increase in biomass will be 330 tons per hectare, and a more conservative indicator is about 150 tons per hectare (Doumett et al., 2011; Filipova et al., 2019).

Paulownia wood is soft, light, with ring-shaped pores, straight-grained with a satin sheen. The average specific weight of wood is 0.35 g/cm^3. Paulownia wood dries easily in air without serious drying defects. It has a high strength-to-weight ratio, a low shrinkage ratio, and is not prone to warping or cracking (Humentyk et al., 2023; Jay 1998). The wood lends itself well to processing. In China and some other Asian countries, paulownia wood is used for a cultivar of purposes, such as furniture, construction, musical instruments, shipbuilding, aviation, packing cases, coffins, paper, plywood, cabinet making, and stucco (Li et al., 2018). Paulownia wood is mainly sold for special products made of solid wood, oriented strand boards, veneer and for the production of pulp for the production of high-quality paper (Yu et al., 2018; Zhang et al., 2022). Its bark was used in Chinese folk medicine as a component of remedies for the treatment of infectious diseases, such as gonorrhea and erysipelas (Zuazo et al., 2013).

Material and Methods

In 2021-2023 field trials were carried out in the experimental field of SPC of Bila Tserkva NAU, situated in the Right-bank Forest-steppe zone – in Bug-Middle Dnipro area. The relief of the experimental field is a slightly-wavy plain with a small slope of the surface from the south to the south-west. In the years when the research was conducted the weather conditions differed from long-term indicators. However, generally they were favourable for the growth and development of paulownia.

The research was conducted according to generally accepted scientific and special agronomic research methods, using computer technology in the processing and analysis of research results. The area of the elementary plot is 120 m^2, repetition is three times. Clone paulownia cultivar was grown In Vitro 112, the scheme of establishing the experiment provided for the planting of plants 4x4 m, with a density of 625 pcs. /ha, as the most optimal and recommended method of obtaining industrial plantations in Ukraine.

Experimental studies were carried out in accordance with the methods of field experiments and the methods of the State Varietal Testing of Agricultural Crops The yield of dry biomass (adjusted to standard humidity) was measured after drying at a temperature of 65 °C to a constant weight. The content of dry matter in biomass was determined after drying at a temperature of 105 °C for 12 hours (in percent). Qualitative characteristics of biomass dry matter, such as the content of cellulose, hemicellulose, lignin and ash, are determined after drying in a muffle furnace at a temperature of 550 +/- 50 °C for 8 hours.

Results and Discussion

Despite the overall efficiency of growing paulownia, the most interesting question is whether the plantations are able to provide a sufficient number of raw materials precisely as a product for further processing into bioenergy in a fairly short period of operation. After all, for Ukraine, the search for fast-growing species that can dramatically increase biomass collection and, accordingly, energy output per hectare of area, compared to other traditional crops of the region, is currently relevant.

Table 1. The influence of the studied factors on the diameter of the trunk of paulownia

Fertilization	Application of cryoprotector	Foliar feeding	2021	2022	2023
Without fertilizer	Without cryoprotector	Without feeding	7.0	11.2	16.1
		Quantum-AmiNoFrost	7.2	11.4	16.2
		SMARTGROW RECOVERY	7.2	11.3	16.3
	Growth regulator cryoprotector MARS EL	Without feeding	7.4	11.5	16.6
		Quantum-AmiNoFrost	7.5	11.7	16.7
		SMARTGROW RECOVERY	7.5	11.7	16.8
Organic fertilizer " Vermicompost "	Without cryoprotector	Without feeding	10.0	12.6	17.8
		Quantum-AmiNoFrost	10.3	12.9	18.1
		SMARTGROW RECOVERY	10.3	12.8	18.2
	Growth regulator cryoprotector MARS EL	Without feeding	10.2	12.9	18.0
		Quantum-AmiNoFrost	10.6	13.2	18.4
		SMARTGROW RECOVERY	10.5	13.1	18.4
SSD $_{0.05}$			0.2	0.4	0.7

Changes in the diameter of the paulownia trunk (Table 1) were determined during its continuous cultivation for three years, i.e. without technical cuts. After all, by analogy with other woody bioenergy crops, the frequency of technical cuts cannot be less than once every three to four years of cultivation.

If we analyze the regularity of the change in the diameter of the paulownia trunk in the first year of its cultivation, then, with an average of 8.8 cm according to the experiment, the plants that were grown with the use of organic fertilizer " Vermicompost " stood out most significantly for the better. Thus, the plants on the options where organic fertilizer was applied had a 3.0 cm thicker trunk, while the difference between the options with or without the use of cryoprotectant was only 0.3 cm, and the foliar fertilizing was 0.2 cm.

Despite the fact that different factors of the experiment had different effects on the formation of the sign of trunk thickness, their overall effect was the best for " Vermicompost " fertilizer, treatment of plants with cryoprotector MARS EL and application of foliar fertilizer Quantum-AminoFrost or SMARTGROW RECOVERY trunk diameter was better according to the experiment - 10.6 and 10.5 cm, respectively.

Since the plants were not cut, in the second year of vegetation, the formation of the trunk thickness depended on the growth of the previous year and the conditions of influence of the factors of the current year. The average diameter of the trunk was 12.2 cm, the use of organic fertilizer helped to obtain a better indicator by 1.5 cm, and cryoprotector - an increase in values by 0.3 cm. Similarly, for the first year of vegetation, the combined combination of organic fertilizer + cryoprotectant + foliar feeding provided better values of the diameter of the trunk of paulownia plants.

In the third year of vegetation, the average diameter of the trunk was 17.3 cm, the use of organic fertilizer helped to obtain a better indicator by 1.7 cm, and cryoprotectant - by 0.4 cm. With " Vermicompost " fertilizer, treatment of plants with MARS EL cryoprotectant and application of foliar fertilizer Quantum-AmiNoFrost or SMARTGROW RECOVERY, the diameter of the trunk was better according to the experiment - 18.4 and 18.4 cm, respectively.

Therefore, for obtaining annual linear increases in the diameter of the trunk, the most significant effect on the trait was observed in the case of the application of such experimental factors as the main fertilization with organic fertilizer " Vermicompost ".

Similarly, as regards the mass of dry matter in paulownia plants - as they grew from year to year, it only accumulated, and changes in the influence factors of the previous year, of course, to a certain extent, were reflected in the indicators of the next growing year (Table 2).

Table 2. The mass of dry matter in one paulownia plant under the influence of factors, kg

Fertilization	Application of cryoprotector	Foliar feeding	2021	2022	2023
Without fertilizer	Without cryoprotector	Without feeding	2.50	11.7	24.0
		Quantum-AmiNoFrost	2.54	11.8	24.3
		SMARTGROW RECOVERY	2.56	11.8	24.3
	Growth regulator cryoprotector MARS EL	Without feeding	2.74	12.2	25.0
		Quantum-AmiNoFrost	2.78	12.3	25.4
		SMARTGROW RECOVERY	2.77	12.3	25.6
Organic fertilizer " Vermicompost "	Without cryoprotector	Without feeding	3.10	13.1	27.8
		Quantum-AmiNoFrost	3.20	13.4	28.2
		SMARTGROW RECOVERY	3.22	13.4	28.0
	Growth regulator cryoprotector MARS EL	Without feeding	3.49	13.9	28.8
		Quantum-AmiNoFrost	3.60	14.2	29.4
		SMARTGROW RECOVERY	3.58	14.1	29.4
	$SSD_{0.05}$		0.2	0.4	0.7

In the first year of vegetation of paulownia plants, it was determined that, as a result, they accumulated 3.0 kg/plant mass of dry matter, at the same time, fertilizer contributed to obtaining a better mass by 0.7 kg/plant, and the cryoprotectant guaranteed an increase of 0.3 kg/plant a plant So, with the combined effect of the factors of the experiment, namely, " Vermicompost " fertilizer, treatment of plants with cryoprotector MARS EL and the use of foliar fertilizer Quantum-AmiNoFrost or SMARTGROW RECOVERY, the mass of dry matter accumulated by one plant was better according to the experiment - 3.60 and 3.58 kg / plant

In the next growing year, the average mass of dry matter in one plant was 12.9 kg/plant, the increase from organic fertilizer was 1.7 kg/plant, and from cryoprotectant - 0.6 kg/plant. However, similarly to the previous year, for the combination of all the factors of the experiment, namely, " Vermicompost " fertilizer, treatment of plants with cryoprotector MARS EL and the use of foliar fertilizer Quantum-AminoFrost or SMARTGROW RECOVERY, the mass of dry matter accumulated by one plant was better according to the experiment - 14.2 and 14.1 kg/plant.

Therefore, in contrast to the first year of vegetation, under the influence of factors, the contribution of organic fertilizers was observed to increase, because plants in the second year of growth need and consume significantly more nutrients to form biomass increments. Also, the increase in the contribution of the cryoprotectant shows that at the beginning of the growing season in the conditions of 2022 there were more days with weather conditions capable of causing stress in plants precisely due to the influence of low air temperatures. And not even frostbite, but a decrease in air temperature at night to 5-8°C, which as a result slows down the linear growth and development of paulownia.

In the third year of vegetation, the average mass of dry matter accumulated in one paulownia plant reached 26.7 kg/plant, and fertilization of plantations with organic fertilizer helped the plants to accumulate 3.8 kg/plant more mass. At the same time, due to the periods with low air temperatures in the spring of 2023, the role of the cryoprotectant increased even more and the options where it was applied provided an increase in dry matter accumulation of 1.2 kg/plant.

It is the complex effect of the research factors, as well as in the first and second year of vegetation, that was the best in terms of effect on the accumulation of dry matter by paulownia plants. So, for the combination of all the factors of the experiment, namely, "Vermicompost" fertilizer, treatment of plants with cryoprotector MARS EL and the use of foliar fertilizer Quantum-AmiNoFrost or SMARTGROW RECOVERY, the mass of dry matter accumulated by one plant was better according to the experiment - 29.4 and 29.4 kg / plant

So, the yield of dry matter obtained per hectare is actually an indicator of the "efficiency of work" of the plant system from an agronomic point of view (Table 3).

Table 3. Yield of dry matter of paulownia under the influence of factors, t/ha

Fertilization	Application of cryoprotector	Foliar feeding	2021	2022	2023
Without fertilizer	Without cryoprotector	Without feeding	1.56	7.30	15.0
		Quantum-AmiNoFrost	1.59	7.36	15.2
		SMARTGROW RECOVERY	1.60	7.40	15.2
	Growth regulator cryoprotector MARS EL	Without feeding	1.71	7.60	15.6
		Quantum-AmiNoFrost	1.74	7.70	15.9
		SMARTGROW RECOVERY	1.73	7.70	16.0
Organic fertilizer "Vermicompost "	Without cryoprotector	Without feeding	1.94	8.20	17.4
		Quantum-AmiNoFrost	2.00	8.40	17.6
		SMARTGROW RECOVERY	2.01	8.40	17.5
	Growth regulator cryoprotector MARS EL	Without feeding	2.18	8.70	18.0
		Quantum-AmiNoFrost	2.25	8.90	18.4
		SMARTGROW RECOVERY	2.24	8.80	18.4
	SSD $_{0.05}$		0.10	0.20	0.37

Thus, according to the results of the first year of vegetation of the paulownia plantations, it was determined that they accumulated a yield of 1.88 t/ha of dry matter, at the same time, the fertilizer contributed to obtaining a better mass by 0.45 t/ha, and the cryoprotectant guaranteed an increase of 0.19 t /Ha.

It was found that due to the combined effect of the factors of the experiment, namely, " Vermicompost " fertilizer, treatment of plants with MARS EL cryoprotectant and the use of foliar fertilizer Quantum-AminoFrost or SMARTGROW RECOVERY, the mass of dry matter accumulated on average by the paulownia plantation was better according to the experiment - 2.25 and 2.24 t/ha.

In the conditions of 2022, the yield of dry matter from the paulownia plantation increased to 8.04 t/ha, the increase from organic fertilizer was 1.06 t/ha, and from the cryoprotectant - 0.39 t/ha. Similarly, to the previous year, the combination of all the factors of the experiment, namely, " Vermicompost " fertilizer, treatment of plants with cryoprotector MARS EL and the use of foliar fertilizer Quantum-AmiNoFrost or SMARTGROW RECOVERY created favorable conditions that ensured the best yield according to the experiment - 8.90 and 8, 80 t/ha.

In the third year of vegetation, the yield of dry matter reached 16.68 t/ha, and fertilization of plantations with organic fertilizer helped plants accumulate 2.40 t/ha more mass. We also observe that, as in the case of the formation of individual dry mass, due to the periods with low air temperatures in the spring of 2023, the role of the cryoprotector increased even more, and the options where it was applied provided an increase in the accumulation of dry matter of 0.73 t/ Ha.

So, it was determined that the complex effect of the research factors, as well as in the first and second year of vegetation, was better in terms of its effect on the formation of dry matter yield by paulownia plants. So, for the combination of all the factors of the experiment, namely " Vermicompost " fertilizer, treatment of plants with MARS EL cryoprotectant and the use of foliar fertilizer Quantum-AmiNoFrost or SMARTGROW RECOVERY, the yield of dry matter was better according to the experiment - 18.4 and 18.4 t/ha.

So, similar to the indicators obtained during the assessment of changes in individual accumulation of dry matter, as the plantations matured, the yield of paulownia increasingly depended on the use of organic fertilizer. Thus, in the first year, the yield increase was only 0.45 t/ha, while in the second year – 1.06 t/ha, and in the third – 2.40 t/ha. At the same time, the role of cryoprotectant is also important to consider, as it determines the resistance of paulownia plants to low temperatures at the beginning of the vegetation period, and the most significant increases from its use were observed in the second (0.39 t/ha) and third years of vegetation (0.73 t/ha) ha), which corresponded to years with short-term decreases in air temperature after the restoration of vegetation of paulownia plants.

In addition, we believe that it is necessary to analyze the qualitative indicators of the content of lignin, cellulose and ash in the obtained raw materials (Table 4).

Table 4. Qualitative indicators of paulownia biomass under the influence of experimental factors, %, average for 2021-2023

Fertilization	Application of cryoprotector	Foliar feeding	Cellulose	Lignin	Ash
Without fertilizer	Without cryoprotector	Without feeding	42.7	20.2	1.10
		Quantum-AmiNoFrost	43.1	19.9	1.07
		SMARTGROW RECOVERY	43.2	19.9	1.10
	Growth regulator cryoprotector MARS EL	Without feeding	43.4	20.5	1.11
		Quantum-AmiNoFrost	43.4	20.5	1.10
		SMARTGROW RECOVERY	43.6	20.0	1.14
Organic fertilizer " Vermicompost "	Without cryoprotector	Without feeding	43.8	20.2	1.11
		Quantum-AmiNoFrost	44.2	20.4	1.14
		SMARTGROW RECOVERY	44.3	20.5	1.10
	Growth regulator cryoprotector MARS EL	Without feeding	44.5	20.4	1.07
		Quantum-AmiNoFrost	44.5	20.5	1.10
		SMARTGROW RECOVERY	44.5	20.7	1.08
	SSD $_{0.05}$		0.32	0.17	0.14

The average cellulose content in paulownia plants according to the experiment was at the level of 43.8%, at the same time, the use of organic fertilizer increased the content by 1.05%, and the treatment of plants with a cryoprotectant contributed to an increase in the cellulose content by 0.41%.

As for the factors of the experiment, the plants felt better from a physiological point of view in all fertilized variants, and therefore higher cellulose content indicators were obtained. At the same time, in the case of a combination of such experimental factors, namely, " Vermicompost " fertilizer and treatment of plants with cryoprotector MARS EL, their effect was enhanced and the cellulose content was better according to the experiment - 44.5%.

The average content of lignin in paulownia plants was 20.3%, and the application of organic fertilizer contributed to an increase of 0.29%, when the use of a cryoprotectant provided the prerequisites for the formation of an increase of 0.24%. At the same time, the best indicators of the content of lignin in plants were obtained in the variant of the experiment for the combination of " Vermicompost " fertilizer, treatment of plants with cryoprotectant MARS EL and the use of foliar fertilizer SMARTGROW RENEWAL - 20.7%.

According to the ash content, the average indicator for the experiment was 1.1%, and the deviations of the characteristic did not depend on the influence of the experimental factors, that is, the use of organic fertilizer or other studied drugs did not affect changes in this quality parameter of plant biomass.

Conclusion

On the third-year paulownia vegetation average diameter trunk was 17.3 cm. Entry organic fertilization provided an increase of 1.7 cm, and the use cryoprotector — by 0.4 cm. Under conditions of optimal combination fertilizer " Vermicompost " (400 kg/ha), processing cryoprotector MARS EL (0.5 l/ha) and foliar feeding SMARTGROW RECOVERY (2.0 l/ha), diameter the trunk reached 18.4 cm.

In the first-year application organic fertilizers contributed to increase masses plants by 0.7 kg/ plant, and the cryoprotector provided an increase of 0.3 kg/ plant. In the second-year increase masses amounted to 1.7 kg/ plant per account fertilizer and 0.6 kg/ plant thanks to cryoprotector. On the third-year average mass dry substances reached 26.7 kg/ plant, of which 3.8 kg were provided fertilizer, and 1.2 kg — cryoprotectant. With increase age the role of organic plants fertilizer in formation biomass markedly was growing

Comprehensive using agrotechnical measures provided the highest productivity. Dry weight substances reached 29.4 kg/ plant, and the yield was: in the first year — 2.25 t/ha, in the second — 8.90 t/ha, in the third — 18.4 t/ha. Organic fertilization contributed to an increase in productivity from 0.45 t/ha in the first year to

2.40 t/ha in the third. Cryoprotector, in particular in years with low temperatures, provided an increase of 0.39 t/ha in the second year and 0.73 t/ha in the third.

Contents cellulose in paulownia plants was 43.8%, but grew to 44.5% under conditions using " Vermicompost " fertilizer (+1.05%) and cryoprotectant (+0.41%). Contents lignin was 20.3%, and the application fertilizer and cryoprotectant increased this indicator by 0.29% and 0.24%, respectively, reaching the maximum value of 20.7%.

References

Abreu M., Reis A., Moura P., Fernando AL, Luís A., Quental L., Patinha P., Gírio F. Evaluation of the Potential of Biomass that Energy in Portugal Conclusions from the CONVERTE Project. Energies 2020, 13, 937.

Candan Z., Gonultas O., Gorgun HV, Unsal O. Examining Parameters of Surface Quality Performance of Paulownia Wood Materials Modified by Thermal Compression Technique. Drv . India 2021, 72, 231–236.

Doumett, S., Azzarello, E., Fibbi, D., Mancuso, S., Mugnai, S., Petruzzelli, G., Del Bubba, M. Influence of the application renewal of glutamate and tartrate on Cd, Cu Pb and Zn distribution between contaminated soil and Paulownia tomentosa in a pilot-scale assisted phytoremediation study. Int. J. Phytoremediation. 2011. No. 13. 1-17.

Filipova L. M., Matskevych V. V., Karpuk L. M., Stadnyk A. P., Andriievsky V. V, Vrublevsky A. T., Krupa N. M., Pavlichenko A. A. Features of Rooting Paulownia in vitro. Egypt.J.Chem . 2019. 57-63.

Humentyk M., Kharytonov M., Shuvar A., Pyrih H., Humentyk V. The growth dynamics of paulownia trees cultivated as energy plantations in the forest-steppe zone of Ukraine. Scientific papers Series B. Horticulture. Volume LXVII, No. 1. 2023. 397-403.

Jay A. Paulownia Plantation Experiences and Profitable Timber Production. Australian Forest Growers, Conference Proceedings, Lismore, 1998. 199-214.

Li H., Jiang X., Ramaswamy HS, Zhu S., Yu Y. High-Pressure Treatment Effects the Density Profile, Surface Roughness, Hardness, and Abrasion Resistance of Paulownia Wood Boards. Trans. ASABE 2018, 61, 1181–1188.

Yu Y., Jiang X., Ramaswamy HS, Zhu S., Li H. Effect of High-Pressure Densification he Moisture Sorption Properties of Paulownia Wood. BioResources 2018, 13, 2473–2486.

Zhang Q., Jin P., Li Y., Zhang Z., Zhang H., Ru G., Jiang D., Jing Y., Zhang X. Analysis of the Characteristics of Paulownia Lignocellulose and Hydrogen Production Potential via Photo Fermentation. Bioresour. Technol. 2022, 344, 126361.

Zuazo VHD, Bocanegra JAJ, Torres FP, Pleguezuelo CRR; Martínez, JRF Biomass Yield Potential of Paulownia Trees in a Semi-Arid Mediterranean Environment (S Spain). Int. J. Renew. Energy Res. IJRER 2013, 3, 789–793.

Understanding soil quality in agricultural land use in Rize province, Türkiye

Dikshya POUDEL [1,2,*], Orhan DENGIZ [2], Sena PACCI [2]

[1] Agricultural University Plovdiv, Plovdiv, Bulgaria

[2] Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Dikshya POUDEL

ikshyapoudel82@gmail.com

Abstract

Soil quality is viewed as a holistic measure of the soil's composition and natural functions, considering its usage and the environmental conditions of the location. Soil quality influences productivity, food safety, health, and environmental quality. It is crucial to assess soil quality to address land-use changes, soil degradation, and to guide sustainable land-use management decisions. The objective of the present study was to determine the soil quality of Rize province, Turkiye using Minimum Data Set (MDS) indicator selection method and two indices model: Integrated Quality Index (IQI) and Nemero Quality Index (NQI). A total of 102 soil samples were collected from the study area and 41 soil properties, encompassing various soil physical, chemical and biological were analyzed. Principal Component Analysis (PCA) was applied to create the MDS, which was then normalized into unitless scores. Subsequently, the IQI and NQI were used to assess soil quality. Soil quality distribution maps were generated based on the results obtained from the model. The average soil quality index from IQI and NQI method was found to be 0.41 and 0.02 respectively. Despite significant differences in values, the quality maps indicated that both soil quality assessment methods produced similar results in representing the study area's quality status. However, comparison with other methods and cross validation of the results using various techniques such as Artificial Neural Networks (ANN), regression analysis, correlation analysis, etc. should be carried out to validate the results obtained from the models and determine the suitable model for soil quality analysis of the given area.

Keywords: Integrated quality index, Minimum data set, Nemero quality index, Soil quality, Soil assessment.

Introduction

Soil quality is viewed as a holistic measure of the soil's composition and natural functions, considering its usage and the environmental conditions of the location. According to The Soil Science Society of America (1997), soil quality is defined as " The capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health". Soil quality impacts soil productivity, food quality and safety, human and animal health and environmental quality(Parr et al., 1992). A wide range of methods which includes, quantitative, semi-quantitative, and qualitative based on field and lab analysis are used to monitor the soil quality of a specific area. Due to budget limitations, the number of soil quality indicators analyzed is often reduced to a minimum dataset. A minimum data set (MDS) is created from different soil properties taken into the study, which are then subjected to unitless scores through normalization and then weighted sum of these properties is calculated(Askari et al., 2015). Integrated Quality Index (IQI) and Nemero Quality Index (NQI) are examples of this calculation. The IQI model, adapted from Doran & Parkin, (1994) soil quality index, represents the sum of weighted values for selected indicators. It combines these metrics into an index using a straightforward equation, applying equal weights to each indicator within the scoring system; in contrast, the NQI model relies on the average and minimum indicator scores without factoring in their weights(Qi et al., 2009a).

Rize Province accounts for 78% of the total tea production in the country, marking it as the leading province in tea cultivation (Borsası, 2014). However, in recent times, the decline in soil fertility and quality is noticed as a significant issue for Turkish tea production. If proper measures are not implemented, the effects of extreme weather events caused by climate change could further impact soil quality. A continuous and detailed soil quality assessment is required for sustainable agriculture production in the province. Thus, we carried out a soil quality assessment study in the micro-catchment areas of the province using NQI and IQI index models by evaluating physical, chemical, and biological soil properties and integrating the obtained data in GIS version 10.7.1 to produce soil quality maps in the study area.

Material and Methods

Study site and Laboratory analysis

Rize province is situated between longitudes 40° 21′ and 41° 25′ E and latitudes 40° 33′ and 41° 20′ N (see Fig. 1). Covering an area of 3920 km^2, the province is predominantly mountainous. The selected study area is considered as the most suitable area for agriculture activities given its cool summers, mild winters, and rainfall throughout the year. 102 sampling sites were chosen randomly on google earth pro after delineating study boarder of the study area. The soil from each sampling site was collected from surface (0-30 cm). Then, the samples were air- dries in the laboratory, pulverized using wooden mallet and sieved through a 2 mm sieve to prepare them for analysis.

Table 1: Soil Analysis Methods for Selected Soil Parameters

Parameters	Protocol	Reference
Aggregate stability (AS)	Wet sieving	Kemper & Rosenau (2018)
Dispersion ratio (DR)	DR= (a/b) * 100	Lal & Elliot (1994)
Erodibility ratio (ER)	ER= (a/b) *(A/c) *100	Lal & Elliot (1994)
Clay ratio (CR)	CR=(100-c)/c	Bouyoucos (1935)
Clay, Silt and Sand)	hydrometer method	Bouyoucos (1951)
Organic Carbon (OC)	Walkley-Black	Nelson & Sommers (1982)
Total N	Kjeldahl	Bremner & Mulvaney, (1982)
Field Capacity	Gravimetric Method	Blake & Hartge (2018)
Base Saturation	Cation Exchange Capacity (CEC) Method	Burt (1992)
Sodium Adsorption Ratio	Saturation extract	Burt (1992)
Bulk Density	Undisturbed soil sample	Burt (1992)
Microbial Biomass Carbon	According to the substrate reduction method	Anderson & Domsch, (1978)
CaCO3	Scheibler calcimeter	Staff (1993)
pH Electrical conductivity	1:2.5 soil:water suspension	Kacar (2009)
NH4OAC-K, Ca, M, Na	Ammonium acetate extraction, flame spectrometry detection	Burt (1992)
DTPA-Cu, Fe, Mn, Zn	DTPA extraction, AAS detection	Lindsey & Norvell (1978)

a is the percentage of silt plus clay in suspension, b is the percentage of silt plus clay dispersed with chemical agent, A is the field capacity, c is t
he percentage of clay dispersed with chemical agent.

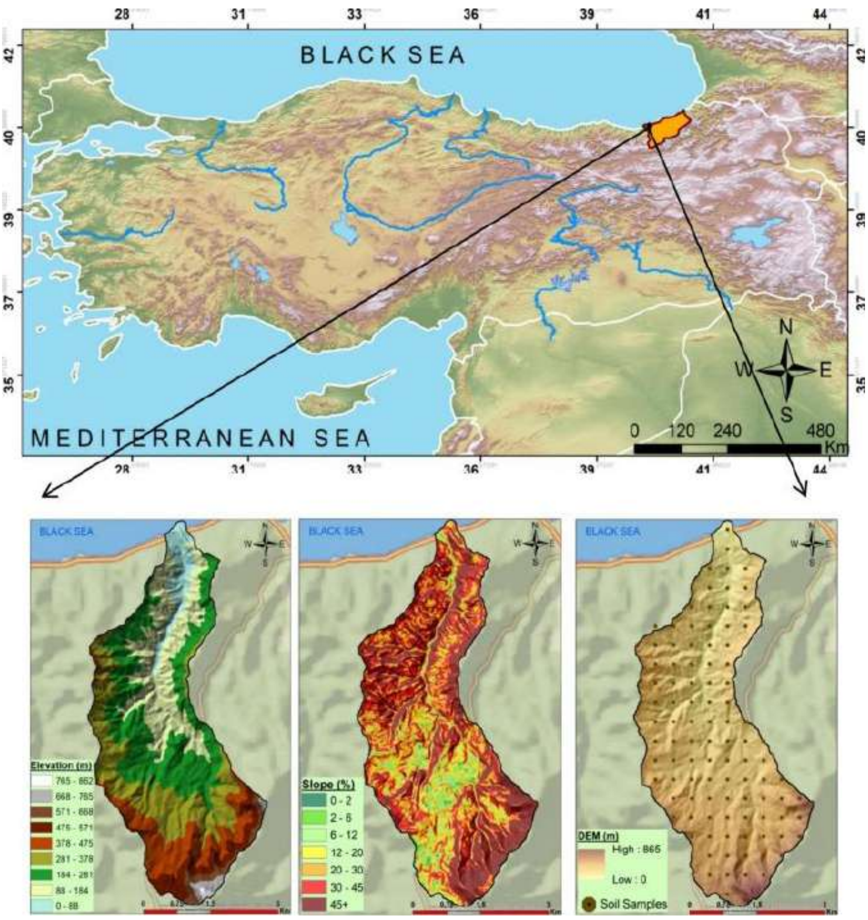


Figure 1: Location, Elevation, Slope and sampling area of the study site

The methods used for the analysis of physical, chemical and biological analysis is summarized in Table 1.

Soil Quality Index Calculation

The Soil Quality Index (SQI) was calculated using three main steps: (i) identifying key indicators for a Minimum Data Set (MDS), (ii) assigning scores to these MDS indicators, and (iii) combining the scores into a single index (Andrews et al., 2002; Karlen & Stott, 2015). In this process, 41 soil properties—covering physical, chemical, and biological aspects—were assessed based on their sensitivity and capacity to capture soil complexity and functionality(Moncada et al., 2014). The principal component analysis(PCA) and factor analysis approach were used to reduce the number of the most appropriate soil quality indicators for the selected study area from the list of all indicators to create a minimum data set (MDS), the detailed procedure described by Andrews et al., (2002). After creating the MDS, the interpretation of the indicators involved transforming the Minimum Data Set (MDS) using a linear scoring function, where each soil parameter is initially given a unitless score on a scale from 0 to 1. The soil parameters then are categorized using three algorithms: (a) 'more is better' (increasing the value of the soil properties improves soil quality), where values were scaled by dividing by the highest value to score up to 1; (b) 'less is better' (increasing the value of the soil properties improves soil quality), where the lowest value was divided by each observation for a maximum score of 1; and (c) 'optimum' (soil properties that positively impact soil quality at optimal level and beyond this level, impacts the quality negatively), which were scored as 'more is better' up to a certain threshold, beyond which they were scored as 'less is better' to avoid negative effects (Karlen & Stott, 2015; Qi et al., 2009;Andrews et al., 2002).

The equations used for scoring soil properties between 0.1 and 1.0, "more is better" (Equation 1), "less is better" (Equation 2) and optimum (Equation 3) and are as follow

$$f\,(x) = \begin{cases} 0.1 & x \geq L \\ 0.9 \times \frac{x-L}{U-L} + 0.1 & L \leq x \leq U \\ 1.0 & x \leq U \end{cases} \tag{1}$$

$$f(x) = \begin{cases} 0.1 & x \geq L \\ 1 - 0.9 \times \frac{x-L}{U-L} + 1 & L \leq x \leq U \\ 1.0 & x \leq U \end{cases} \quad (2)$$

The final step in assessing soil quality involved combining the selected indicators into a single soil quality index. Here two different soil quality indices (IQI and NQI) were applied to assess the soil quality, which were calculated using equations (3)(Doran & Parkin, 2015) and (4)(Han & Wu, 1994) respectively.

$$IQI = \sum_{i=1}^{n} NiWi \quad (3)$$

Where, n is the number of factors, Ni is the score value or score assigned to each factor, Wi is the weight of each factor.

For determining weight for each MDS parameter, weights were assigned based on PCA results by dividing the percentage of variance explained by each principal component (PC) by the cumulative variance of all selected PCs to calculate the Soil Quality Index (SQI)(Biswas et al., 2017).

$$NQI = \sqrt{P_{ave}^2 + P_{min}^2/2} \times n - 1/n \quad (4)$$

Where, P_{ave} is the average scores of the selected factors in each site, P_{min} is the minimum scores of the selected factors in each site and n is the number of factors.

Results and Discussion

Minimum Data Set based on Principal Component Analysis

From the PCA analysis, only principal components (PCs) with eigenvalues of 1 or higher were considered for the minimum data set (MDS). Varimax rotation was operated to the factors with eigenvalues higher than 1 in order to retain minimum no. of parameters in the MDS. Withing each PC, indicators with loading values within 10% of the highest loading were selected for inclusion in the MDS. The multiple variables that were retained within a single PC, their correlations were analyzed and the parameter having the highest correlation loading was selected in the MDS (Qi et al., 2009). The application of PCA to our dataset with 41soil properties resulted in the formation of minimum dataset with 10 properties viz. ER, field capacity, organic carbon, CEC, microbial carbon-to-organic carbon ratio, base saturation, Fe, Cu, SAR, and P. The calculated principal components explained 79.58% of the total variance, as indicated in Table 3.

Table 2: Principal Components and Parameters selection for MDS

Parameters	PC-1	PC-2	PC-3	PC-4	PC-5	PC-6	PC-7	PC-8	PC-9
Total	6.88	5.64	5.42	2.73	2.43	1.89	1.87	1.79	1.57
Variance %	18.12	14.83	14.27	7.20	6.40	4.99	4.93	4.69	4.13
Cumulative %	18.12	32.96	47.22	54.42	60.83	65.83	70.75	75.45	79.58
Sand %	-0.956	0.127	0.030	-0.105	0.084	0.044	0.009	0.063	-0.053
Clay %	**0.934**	-0.061	-0.115	0.003	-0.133	-0.073	0.077	0.065	-0.159
Permanent Wilting Point	**0.887**	-0.180	0.280	0.035	-0.083	0.010	0.125	0.104	-0.074
Clay ratio	-0.868	0.169	0.047	-0.089	0.140	-0.022	-0.136	-0.139	0.150
Feld Capacity	**0.863**	-0.242	0.351	0.061	-0.023	0.043	0.085	0.075	0.071
Hydraulic conduc.(mm/h)	-0.806	0.043	0.445	-0.041	0.169	0.077	-0.067	-0.069	0.185
SSI %	0.701	-0.066	0.386	0.063	0.052	0.035	-0.096	-0.049	-0.344
Available Water Capacity	0.627	-0.302	0.404	0.095	0.093	0.094	-0.009	0.005	0.324
Silt %	0.488	-0.185	0.151	0.247	0.055	0.035	-0.172	-0.277	0.436
Total Basic Cation	-0.146	**0.951**	-0.103	0.057	-0.029	0.030	0.006	0.042	0.050
Base Saturation	-0.160	**0.929**	-0.167	0.034	0.022	0.013	-0.134	0.029	0.036
Ca ppm	-0.123	**0.872**	0.008	-0.044	-0.024	-0.012	-0.041	-0.038	0.026
Mg ppm	-0.263	0.763	-0.243	-0.127	0.117	0.054	0.051	-0.116	0.055
pH	-0.237	0.729	-0.304	-0.253	0.233	0.028	-0.010	-0.084	-0.060
OM%	0.137	-0.221	**0.856**	0.014	0.157	0.166	0.214	0.084	0.097
Bulk Density	-0.082	0.257	-0.856	-0.056	-0.127	-0.175	-0.078	-0.025	-0.252
OC %	0.140	-0.237	**0.851**	0.018	0.153	0.168	0.216	0.087	0.099
AS %	-0.060	-0.020	0.770	-0.087	0.101	-0.069	0.019	-0.006	-0.276

N (ppm)	0.053	-0.081	0.574	0.231	0.059	0.268	0.003	-0.157	-0.262
P2O5 (ppm)	0.157	-0.170	0.060	**0.866**	0.105	0.186	0.072	0.071	-0.030
P (ppm)	0.157	-0.170	0.060	**0.866**	0.105	0.186	0.072	0.071	-0.030
K (me/100g)	0.143	0.423	-0.040	0.616	-0.159	-0.029	-0.003	0.329	-0.058
(qCO2)	0.277	-0.101	-0.028	-0.440	-0.247	0.180	-0.112	0.356	-0.009
Microbial Biomass Carbon	-0.166	0.126	0.423	0.066	**0.844**	0.090	-0.047	-0.058	-0.017
Microbial C /Organic C	-0.129	-0.005	0.491	0.119	**0.807**	0.091	-0.033	-0.028	0.007
Soil Respiration (CO2)	-0.327	0.396	-0.284	-0.024	0.704	0.040	-0.135	-0.155	-0.056
CaCO3 %	-0.055	0.209	-0.147	-0.231	-0.388	0.080	-0.223	-0.205	-0.068
Fe (ppm)	0.046	-0.069	0.397	0.246	-0.026	**0.741**	-0.003	0.076	-0.035
Cu (ppm)	-0.036	0.530	0.057	0.073	0.059	**0.705**	-0.079	-0.076	-0.069
Zn (ppm)	0.058	0.129	0.360	0.237	0.104	0.534	-0.069	-0.135	-0.058
Mn (ppm)	0.321	0.280	0.066	0.229	-0.051	-0.485	-0.217	-0.147	-0.128
CEC (mek/100g)	0.154	-0.011	0.287	0.132	-0.090	-0.002	0.875	-0.028	0.019
Hydrogen me/100g	0.205	-0.497	0.295	0.082	-0.061	-0.017	0.733	-0.045	-0.009
EC (µS/cm)	0.079	-0.328	0.301	0.019	-0.160	0.013	-0.439	0.196	0.012
Sodium Adsorption Ratio	0.099	-0.357	0.124	0.036	-0.075	-0.060	-0.078	0.809	0.009
Na (me/100g)	0.018	0.403	-0.077	0.346	0.071	0.028	-0.048	0.713	0.032
Erodibility ratio	-0.421	0.081	0.020	-0.129	0.016	-0.073	0.050	0.114	0.685
Dispersion ratio %	-0.367	0.226	-0.510	-0.054	-0.088	-0.044	0.017	-0.100	0.560

Determining the weights of parameters in the minimum data set and scoring the parameters

After MDS was created, selected parameters were given scoring using functions from equation 1 and 2 based on whether the nature of the parameter. The influence of each feature in soil quality models is determined by the weight assigned to it. Features with higher weights in the MDS have a greater impact on the soil quality model, while those with lower weights contribute less (Mukherjee et al., 2014). According to the weight calculations in the MDS, the organic carbon parameter had the highest weight, whereas cation exchange capacity had the lowest weights. Likewise, while assigning the score for each parameter, function from equations 1 and 2 were used. For erodibility ratio and sodium adsorption ratio, scoring was done using less is better function, while more is better function was applied for other parameters in the MDS. The score obtained then was multiplied with the communalities of each parameter. The communalities resulting from factor analysis is shown in Table 4., and the soil quality according to Integrated Quality and Nemero Quality Indices were calculated using equations 3 and 4, respectively.

Table 3: Calculated communality and weight values for each soil quality indicator included under MDS

Parameters	Communality	Weight
Microbial Carbon/Organic Carbon	0.601	0.101
P (ppm)	0.352	0.056
Sodium absorption ratio	0.349	0.059
Base Saturation	0.679	0.114
Organic Carbon %	0.797	0.134
Fe ppm	0.681	0.114
Cu ppm	0.783	0.132
Cation Exchange Capacity	0.261	0.044
Erodibility ratio	0.732	0.123
Field Capacity	0.688	0.116

Soil Quality Distribution Maps

The soil quality maps generated after the application of IQI and NQI model is depicted in figures 2 and 3.

In the IQI map, the lowest to the highest soil quality ranges from 0.458 to 0.322, while it ranges from 0.0215 to 0.0308 in the NQI map. Despite the significant difference in values that range from high to low, the quality maps indicated that both soil quality assessment methods produced similar results in representing the quality status of the study area, demonstrating that the two methods effectively and accurately assess soil quality across the study area. In both the maps, it is found that the study site had high quality soil in the southern part, whereas lower soil quality was confined to the northern site. Lower-quality regions are scattered in the northern parts, likely due to factors such as low organic matter, moisture content, and high sand, sodium, bulk density, and hydraulic conductivity. These conditions degrade soil properties like aggregate stability, structural integrity, and microbial biomass carbon.

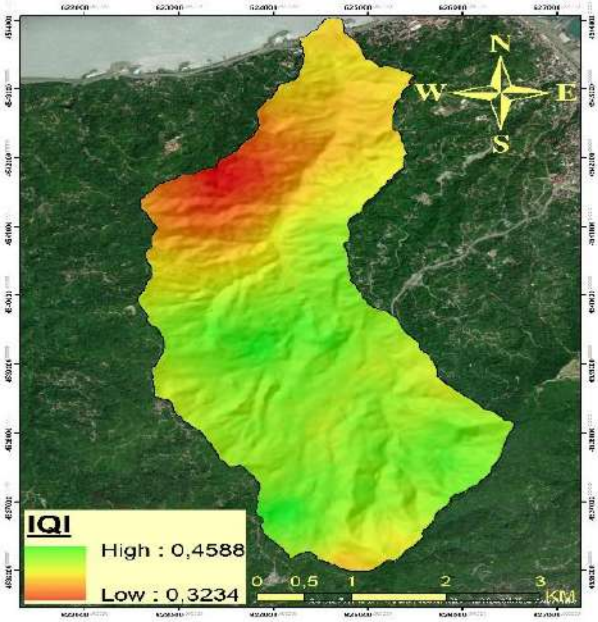


Figure 2: IQI-soil quality map

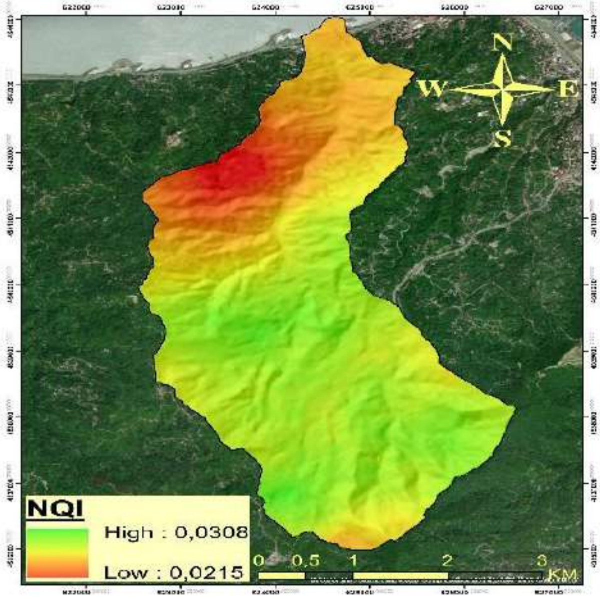


Figure 3: NQI-soil quality map

The IQI model assigns different weights to indicators, emphasizing key ones for determining soil quality. In contrast, the NQI model treats all indicators equally, except for the lowest-scoring one, which is weighted more by adding it to the average score (Qi et al., 2009). In this study, cross validation using other approaches such as regression, correlation, etc., wasn't carried out to predict most suitable model for soil quality assessment. In the research carried out by Qi et al., (2009) NQI showed good agreement in match analysis, its agreement percentage in direct comparison and Kappa analysis was lower than IQI. Additionally, IQI demonstrated stronger correlation coefficients and a linear slope closer to 1, indicating higher accuracy. Thus, methods and cross validation of the results using various techniques such as Artificial Neural Networks (ANN), regression analysis, correlation analysis, etc. should be carried out to validate the results obtained from the models and determine the suitable model for soil quality analysis of the given area.

Microbial activity is a critical factor in shaping the chemical profile of mineral water sources. Soil microorganisms mediate a variety of geochemical processes that influence the concentration of specific ions in groundwater. Microbes can influence the redox potential of the soil, affecting the solubility of redox-sensitive elements like iron, manganese, and sulfur (Carter & Gregorich, 2007). For example, Sulfate-reducing bacteria can convert sulfate (SO_4^{2-}) to sulfide (S^{2-}), affecting the sulfate levels in mineral waters. This process is common in anaerobic conditions where organic matter is abundant. Iron and manganese-oxidizing bacteria play a role in the redox reactions of these metals. In oxygen-poor environments, microbes can reduce insoluble ferric (Fe^{3+}) and manganic (Mn^{4+}) oxides to soluble ferrous (Fe^{2+}) and manganous (Mn^{2+}) forms, respectively, increasing their concentrations in mineral water.

Conclusion

This study highlights that soil quality indices can yield comparable results even with different models. The soil quality indices values obtained from the IQI and NQI model differed but the soil quality maps revealed similar results in depicting soil quality status of the study area. However, for a method to become a standard, it must be fast, reliable, and cost-effective and the MDS indicator method applied in the study meets these criteria. Careful selection of indicators for the MDS is crucial, and further research should focus on refining these models, validating the results obtained from the models in order to enhance its suitability for global adoption.

References

America, S. S. S. of. (1997). Glossary of soil science terms.

Anderson, J. P. E., & Domsch, K. H. (1978). Mineralization of bacteria and fungi in chloroform-fumigated soils. Soil Biology and Biochemistry, 10(3), 207–213.

Andrews, S. S., Karlen, D. L., & Mitchell, J. P. (2002). A comparison of soil quality indexing methods for vegetable production systems in Northern California. Agriculture, Ecosystems & Environment, 90(1), 25–45. https://doi.org/10.1016/S0167-8809(01)00174-8

Askari, M., O'Rourke, S., & Holden, N. (2015). Evaluation of soil quality for agricultural production using visible–near-infrared spectroscopy. Geoderma, 243. https://doi.org/10.1016/j.geoderma.2014.12.012

Biswas, S., Hazra, G. C., Purakayastha, T. J., Saha, N., Mitran, T., Singha Roy, S., Basak, N., & Mandal, B. (2017). Establishment of critical limits of indicators and indices of soil quality in rice-rice cropping systems under different soil orders. Geoderma, 292, 34–48. https://doi.org/10.1016/j.geoderma.2017.01.003

Blake, G. R., & Hartge, K. H. (2018). Particle Density. In A. Klute (Ed.), SSSA Book Series (pp. 377–382). Soil Science Society of America, American Society of Agronomy. https://doi.org/10.2136/sssabookser5.1.2ed.c14

Borsası, R. T. (2014). Doğu Karadeniz Bölgesi Tarım Ürünleri Raporu. Rize: Rize Ticaret Borsası.

Bouyoucos, G. J. (1935). The Clay Ratio as a Criterion of Susceptibility of Soils to Erosion1. Agronomy Journal, 27(9), 738–741. https://doi.org/10.2134/agronj1935.00021962002700090007x

Bouyoucos, G. J. (1951). A recalibration of the hydrometer method for making mechanical analysis of soils. https://www.cabidigitallibrary.org/doi/full/10.5555/19521900093

Bremner, J. M., & Mulvaney, C. S. (1982). Nitrogen—Total. In A. L. Page (Ed.), Agronomy Monographs (1st ed., Vol. 9, pp. 595–624). Wiley. https://doi.org/10.2134/agronmonogr9.2.2ed.c31

Burt, R. (1992). Soil survey laboratory methods manual. USDA. https://library.wur.nl/WebQuery/titel/596879

Burt, R. (2014). SOIL SURVEY LABORATORY METHODS MANUAL.

Calculating Cation Exchange Capacity, Base Saturation, and Calcium Saturation. (2019, August 22). https://ohioline.osu.edu/factsheet/anr-81

Chandrakala, M., Ramesh, M., Sujatha, K., Hegde, R., & Singh, S. K. (2018). Soil fertility evaluation under different land use system in tropical humid region of Kerala, India. International Journal of Plant & Soil Science, 24(4), 1–13.

Doran, J. W., & Parkin, T. B. (1994). Defining and Assessing Soil Quality. In J. W. Doran, D. C. Coleman, D. F. Bezdicek, & B. A. Stewart (Eds.), SSSA Special Publications (pp. 1–21). Soil Science Society of America and American Society of Agronomy. https://doi.org/10.2136/sssaspecpub35.c1

Doran, J. W., & Parkin, T. B. (2015). Defining and Assessing Soil Quality. In J. W. Doran, D. C. Coleman, D. F. Bezdicek, & B. A. Stewart (Eds.), SSSA Special Publications (pp. 1–21). Soil Science Society of America and American Society of Agronomy. https://doi.org/10.2136/sssaspecpub35.c1

Han, W. J., & Wu, Q. T. (1994). A primary approach on the quantitative assessment of soil quality. Chin. J. Soil Sci, 25, 245–247.

Kacar, B. (2009). Soil analysis. Nobel Publication (Extended Edition II) No, 1387, 467.

Karlen, D. L., & Stott, D. E. (2015). A Framework for Evaluating Physical and Chemical Indicators of Soil Quality. In J. W. Doran, D. C. Coleman, D. F. Bezdicek, & B. A. Stewart (Eds.), SSSA Special Publications (pp. 53–72). Soil Science Society of America and American Society of Agronomy. https://doi.org/10.2136/sssaspecpub35.c4

Kemper, W. D., & Rosenau, R. C. (2018). Aggregate Stability and Size Distribution. In A. Klute (Ed.), SSSA Book Series (pp. 425–442). Soil Science Society of America, American Society of Agronomy. https://doi.org/10.2136/sssabookser5.1.2ed.c17

Lal, R., & Elliot, W. (1994). Erodibility and Erosivity. In Soil Erosion Research Methods (2nd ed.). Routledge.

Lindsey, W. L., & Norvell, W. A. (1978). Analysis of micronutrients. Soil Sci. Soc. Am, 42, 421–448.

Moncada, M. P., Gabriels, D., & Cornelis, W. M. (2014). Data-driven analysis of soil quality indicators using limited data. Geoderma, 235, 271–278.

Nelson, D. W., & Sommers, L. E. (1982). Total Carbon, Organic Carbon, and Organic Matter. In A. L. Page (Ed.), Agronomy Monographs (1st ed., Vol. 9, pp. 539–579). Wiley. https://doi.org/10.2134/agronmonogr9.2.2ed.c29

Parr, J. F., Papendick, R. I., Hornick, S. B., & Meyer, R. E. (1992). Soil quality: Attributes and relationship to alternative and sustainable agriculture. American Journal of Alternative Agriculture, 7(1–2), 5–11. https://doi.org/10.1017/S0889189300004367

Qi, Y., Darilek, J. L., Huang, B., Zhao, Y., Sun, W., & Gu, Z. (2009a). Evaluating soil quality indices in an agricultural region of Jiangsu Province, China. Geoderma, 149(3), 325–334. https://doi.org/10.1016/j.geoderma.2008.12.015

Staff, S. S. (1993). Soil survey manual USDA handbook No 18. US Government Printing Office, Washington, DC.

Wang, X., & Gong, Z. (1998). Assessment and analysis of soil quality changes after eleven years of reclamation in subtropical China. Geoderma, 81(3), 339–355. https://doi.org/10.1016/S0016-7061(97)00109-2

Wilding, L. P. (1985). Spatial variability: Its documentation, accommodation and implication to soil surveys. https://www.cabidigitallibrary.org/doi/full/10.5555/19851900446

Zahedifar, M. (2023). Assessing alteration of soil quality, degradation, and resistance indices under different land uses through network and factor analysis. CATENA, 222, 106807. https://doi.org/10.1016/j.catena.2022.106807

Reactions of some spinach cultivars against beet necrotic yellow vein virus

Abide ESER, Nazli Dide KUTLUK YILMAZ[1]
[1]Ondokuz Mayis University, Agricultural Faculty, Department of Plant Protection, Samsun, Türkiye

***Corresponding Author**

Nazli Dide KUTLUK YILMAZ
nazlik@omu.edu.tr

Abstract

Beet necrotic yellow vein virus (BNYVV), the causal agent of rhizomania disease, provokes lateral root proliferation and restricts the main root growth of sugar beet. The virus is in vivo-transmitted by the zoospores and persists in soil via long-lasting cystosori of Polymyxa betae. This study was carried out under controlled conditions to determine the reactions of different spinach cultivars against BNYVV. For this purpose, eight hybrid spinach cultivars (Sogocoyati, Ulak, Matador, El-Hayat, El-Lucio, Tragopan, SV2580VC and Novica) were grown according to the bait plant test method in three replications in a soil sample taken from a field known to be infested with BNYVV in Samsun province. Additionally, a non-infected soil sample was taken from a field in Samsun province where rhizomania disease was not observed and not detected, and each cultivar was grown in this soil sample in two replications. After the growing period of six weeks, each pot was harvested separately, and total plant and root weight of each pot was determined. Then, both leaf and root samples of each cultivar were taken from per pot, and the presence of BNYVV was investigated by ELISA method. The roots of all spinach cultivars, except Novica F1 cultivar, were found to be infected with BNYVV. Interestingly, no BNYVV infection was detected in the leaves of any of the spinach cultivars examined in this study. On the other hand, among BNYVV-infected cultivars, the highest decrease in plant weight was found in cv. Matador with 94%, and the highest decrease in root weight was found in cv. Trogopan and cv. Matador with 99% compared to healthy control.

Keywords: Rhizomania, BNYVV, ELISA, plant weight, root weight

Introduction

Spinach (*Spinacia oleracea L.*) is an important winter vegetable in the Amaranthaceae family, grown worldwide primarily for its edible leaves. Türkiye makes significant contribution to this production and ranks fourth worldwide after China, USA and Japan with an annual production of 232,699 tonnes (FAO, 2021; TUIK, 2023).

There are many fungal, bacterial and viral disease agents that adversely affect spinach production (Correll et al., 1994). Although many viral agents have been reported in spinach plants (Brunt et al., 1996), some viruses of economic importance include cucumber mosaic virus (CMV), turnip mosaic virus (TuMV), tobacco mosaic virus (TMV), tomato spotted wilt virus (TSWV), beet curly top virus (BCTV), beet mosaic virus (BtMV), lettuce mosaic virus (LMV) and beet necrotic yellow vein virus (BNYVV) (Smith et al., 1988; Fotopoulos et al, 2011). Among these viruses, BNYVV has a different importance from the others since it is transmitted by a soil-borne protist vector *Polymyxa betae* Keskin (Putz et al., 1990). The virus can survive inside the thick-walled resting spores (cystosori) of the vector in soil for at least 15 years. After taking up once, protist vector has carried the virus for a long time (Rush and Heidel, 1995).

The host range of BNYVV is relatively narrow. In addition to sugar beet, the virus infects fodder beet, Swiss chard, red table beet and spinach in nature (Rezende et al., 2015; Tamada, 2016). BNYVV causes rhizomania, one of the most economically important diseases of sugar beet (*Beta vulgaris L.*) worldwide. Typical symptoms of the disease are characterized by a massive proliferation of lateral roots and constricted growth of tap root resulting in reduction in the sugar content (Rush and Heidel, 1995). In spinach plant, BNYVV causes vein clearing and chlorotic lesions on the leaves; these infected leaves harden, wrinkle and the lesions become necrotic in time. Even stunting, wilting and death of the plant can be observed (Mou et al., 2012). BNYVV mostly causes systemic infection in spinach plants (Tamada and Baba, 1973; Gilmer, 2016).

In Türkiye, BNYVV has been found to cause infection in spinach production areas in the Aegean, Marmara and Black Sea Regions (Gümüş et al., 2014; Güngör et al., 2017; Bağlan and Korkmaz, 2019; Karanfil et al., 2024). However, there is no information on the reactions of different commercially available spinach cultivars to BNYVV in Türkiye. This study was carried out to evaluate the interactions between different hybrid spinach cultivars and BNYVV population, which were obtained from Samsun province, and to determine the effect of BNYVV on some plant parameters under controlled conditions.

Material and Methods

Spinach Cultivars

In this study, eight different hybrid spinach cultivars were used (Table 1).

Table 1. Spinach cultivars used in bait plant test studies

No	Cultivar	Company	No	Cultivar	Company
1	Sogocoyati F1	Sgaravatti	5	Novico F1	Nunhems
2	Ulak F1	Zeta	6	El-Lucio F1	Syngenta
3	Matador F1	Biotek	7	Tragopan RZ F1	Rijk Zwaan
4	El-Hayat F1	Syngenta	8	SV 3580 VC F1	Seminis

Soil samples and bait plant experiment

A soil sample infested with BNYVV and *P. betae* was collected from a field in Bafra district of Samsun province in 2023. An uninfected soil sample for the healthy control treatment was collected from a field in Samsun province where rhizomania disease was not seen and detected.

BNYVV infested soil sample was homogenized and mixed with sterile sand (1 part of soil: 4 parts of sand). Besides this, sterilized uninfested soil and sand mixture was used as the healthy control for all spinach cultivars with two replications in the bait plant experiment. Sugar beet (BNYVV susceptible cv. Ansa) was also included in the trial as a positive control. Then, five seeds were planted in 300-ml plastic pots containing a mixture of soil and sterile sand. The plants were grown under controlled conditions of 12-h photoperiod, at 20°C (night) and 25°C (day) temperatures and watered with Hoagland's solution as needed. The experiment was carried out in a randomized block design with three replications. After six weeks growth, the number of plants per pot was determined, their roots were carefully washed under running tap water, and all plants of each pot were combined, and then weighted. The collected root and leaf samples were then used to determine the presence of BNYVV by ELISA.

Phenotypic assessment of spinach cultivars

Before harvesting, spinach plants in all replicates of different cultivars were individually assessed for virus symptoms and photographed.

Serological Tests

A double antibody sandwich-enzyme linked immunosorbent assay (DAS-ELISA) was performed to test the samples for BNYVV using commercial kits (Bioreba) following the manufacturer's instructions. In the ELISA tests, both leaf and root samples obtained from the bait plant test of each cultivar were used. Absorbance readings at 405 nm were obtained 2 h after substrate incubation by using a microplate reader (Tecan Spectra II), and the samples were considered positive when the absorbance values were two times more than the mean value of the healthy controls (Karanfil et al., 2024).

Results And Discussion

At the end of six weeks growing period, both leaf and root samples of different spinach cultivars were tested for the presence of BNYVV by ELISA method. The roots of all spinach cultivars, except cv. Novica, were found to be infected with BNYVV. The roots of cv. Novica had absorbance value of 0.327, suggesting a lower titer of BNYVV in this cultivar than the others cultivars (0.483-1.163). Besides this, the highest BNYVV titre was obtained from the roots of cv. EL-Hayat (1.163) (Fig. 1). On the other hand, no BNYVV infection was detected in the leaves of any of the hybrid spinach cultivars examined in this study. Additionally, the leaves of BNYVV-infected spinach cultivars did not show any visible symptom in bait plant test. Similarly, Mou et al. (2012) reported that the roots of spinach plants can be infected with BNYVV even if leaf symptoms are not observed. Also, rhizomania-resistant sugar beet plants have reduced accumulation of BNYVV in small rootlets, inhibition of the virus spread to the taproot, and a lack of rootlet proliferation and other symptoms (Scholten et al., 1994; Heijbroek et al., 1999). In this study, the BNYVV population of Samsun province did not cause neither symptom development nor BNYVV infection on leaves of different spinach cultivars.

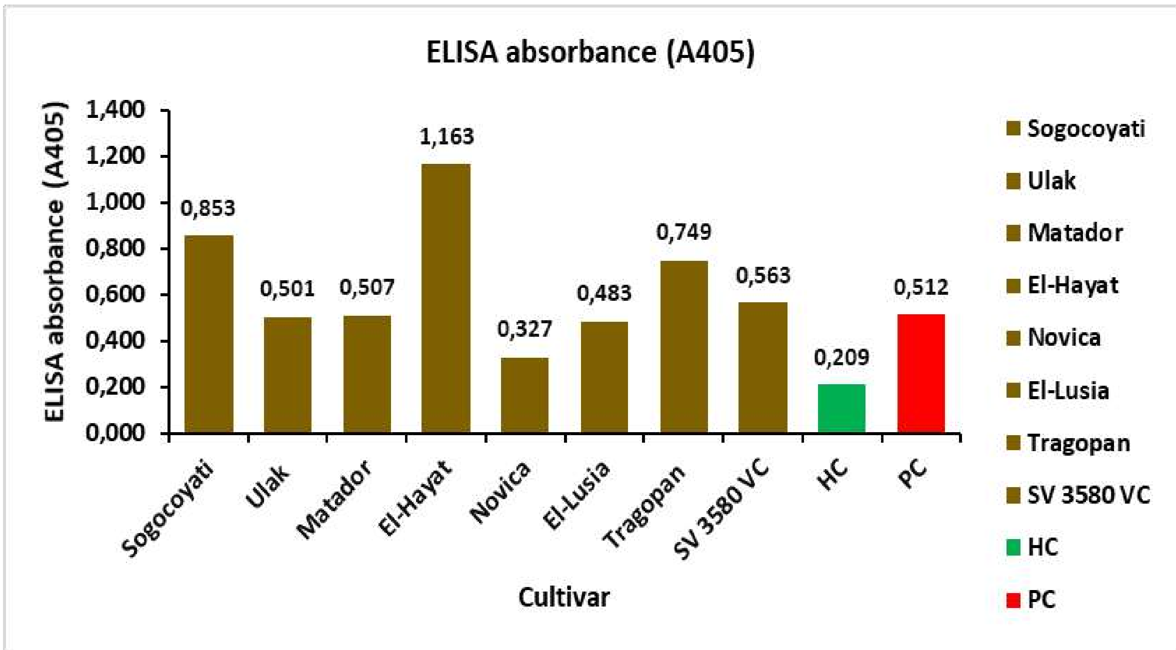


Figure 1. The mean titres of beet necrotic yellow vein virus (BNYVV) detected by ELISA according to spinach cultivars of bait plant roots [HC: healthy control (spinach root), PC: positive control (sugar beet root)]

According to the results of our study, BNYVV can be considered to have impact on both plant and root weight in different spinach cultivars. In this study, in BNYVV-infected cultivars, the highest decrease in plant weight was found in cv. Matador with 94% (Fig. 2) and the highest decrease in root weight was found in cv. Trogopan and cv. Matador with 99% compared to healthy control (Fig. 3). Indeed, it was reported that BNYVV infection resulted in an increase in the number of lateral roots and leaves and a decrease in leaf weight in infected spinach cultivars compared to healthy plants (Mou et al., 2012). Furthermore, Mou et al. (2012) reported that there was no significant difference in total leaf, root and plant weights between plants with and without leaf symptoms.

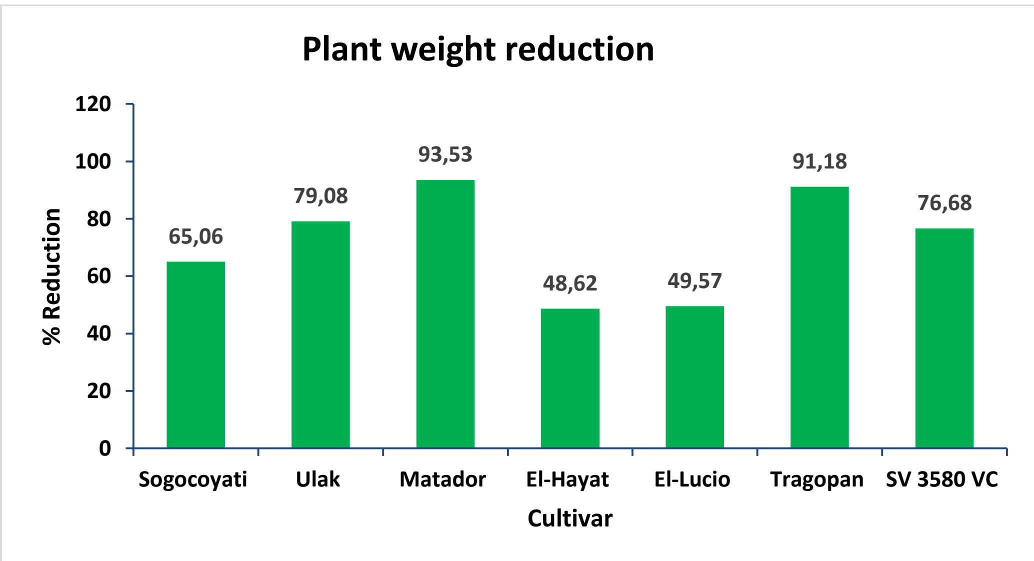


Figure 2. Percentage decreases in plant wet weight of BNYVV-infected different spinach cultivars compared to healthy control

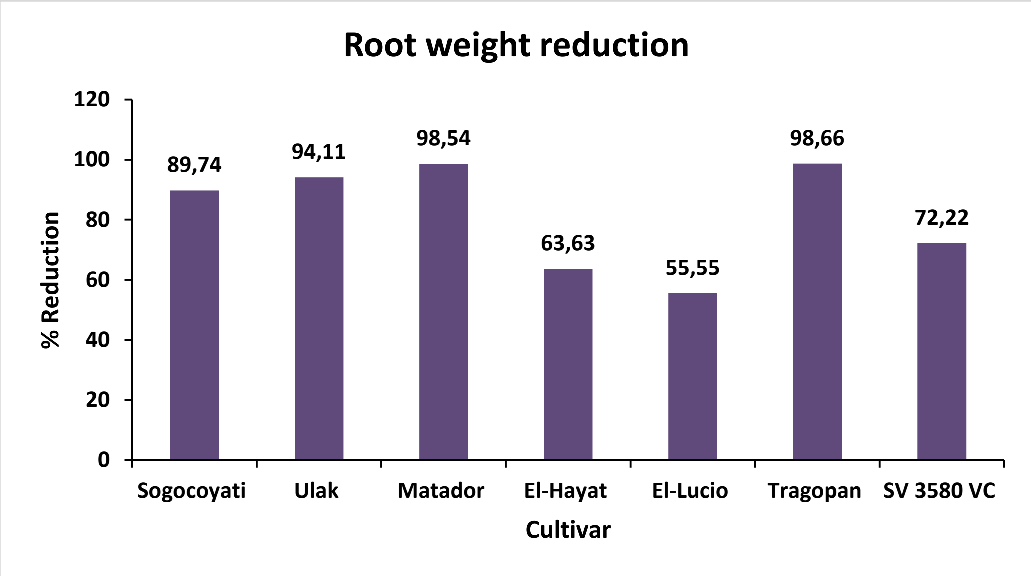


Figure 3. Percentage decreases in root wet weight of BNYVV-infected different spinach cultivars compared to healthy control

Conclusion

In spinach is an important vegetable species with its high nutritional value content. Viruses cause economic losses in spinach and BNYVV is among them. In this study, the reactions of some commercial spinach cultivars against BNYVV isolate obtained in Samsun province were investigated. The roots of all spinach cultivars, except cv. Novica, were found to be infected with BNYVV, whereas leaves of spinach cultivars were not. In this study, genetic variability against BNYVV was detected in a limited number of spinach cultivars. A comprehensive screening of spinach genetic resources is needed to identify potential sources of resistance to BNYVV.

References

Bağlan, Z., Korkmaz, S., 2019. Çanakkale ili ıspanak üretim alanlarında pancar nekrotik sarı damar virüsü (Beet Necrotic Yellow Vein Virus; BNYVV)'nün tespiti ve moleküler karakterizasyonu. Çanakkale Onsekiz Mart Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 5 (2), 278-292.

Brunt, A.A., Crabtree, K., Dallwitz, M.J., Gibbs, A.J., Watson, L., 1996. Viruses of plants: Descriptions and lists from the VIDE Database. CAB International Publishing, Wallinford, UK. p. 1484.

Correll J.C., Morelock, T.E., Black, M.C., Koike, S.T., Brandenberger, L.P., Dainello, F.J., 1994. Economically important diseases of spinach. Plant Disease, 78, 653- 660

FAO, 2024. https://www.fao.org/faostat/en/#data (Erişim: 10.12.2024)

Fotopoulos, V., Dovas, C.I., Katis, N.I., 2011. Incidence of viruses infecting spinach in Greece, highlighting the importance of weeds as reservoir hosts. Journal of Plant Pathology, 93, 389-395.

Gilmer, D., 2016. Molecular biology and replication of beet necrotic yellow vein virus. Rhizomania, 85-107.

Gümüş, M., Erbay, E., Erkan, S., Paylan, İ.C., 2014. Occurrence of viruses infecting spinach in Western Anatolia of Turkey: the first field survey report. Journal of Food, Agriculture and Environment, 12, 272-275.

Güngör, M., Uzunbacak, H., Kutluk Yilmaz, N.D., Şevik, M.A., 2017. Samsun ili ıspanak üretim alanlarında enfeksiyon oluşturan virüslerin belirlenmesi, Ondokuz Mayıs Üniversitesi, Ziraat Fakültesi, Anadolu Tarım Bilimleri Dergisi, 32, 164-168.

Heijbbroek, W., Musters, P.M.S., and Schoone, A.H.L., 1999. Variation inpathogenicity and multiplication of Beet necrotic yellow vein virus (BNYVV) in relation to the resistance of sugar beet cultivars. Eur. J. PlantPathol. 105: 397-405.

Karanfil, A., Randa-Zelyüt, F., Korkmaz, S., 2024. Determination of Benyvirus necrobetae (Beet Necrotic Yellow Vein Virus) infection from spinach fields of South Marmara Region in Türkiye. International Journal of Nature and Life Sciences, 8 (2), 132-137.

Mou, B., Richardson, K., Benzen, S., Liu, H.Y., 2012. Effects of Beet necrotic yellow vein virus in spinach cultivars. Plant disease, 96 (5), 618-622.

Putz C., Merdinoğlu O., Lemaire O., Stocky G., Valentin P., Wiedemann S., 1990. Beet Necrotic Yellow Vein Virus, Causal Agent of Sugar Beet Rhizomania. Rew .Pl. Path., 69 (5): 247-254.

Rezende, J.A.M., Camelo, V.M., Flôres, D., Mello, A.P.D.O.A., Kitajima, E.W., Bedendo, I.P., 2015. First Report of Beet necrotic yellow vein virus on Red Table Beet in Brazil. Plant Disease, 99 (3), 423-423.

Rush, C.M., G.B. Heidel., 1995. Furovirus disease of sugar beets in the United States. 868-875.

Scholten, O.E., Paul, D., van Lent, J.W.M., Goldbach, R.W., 1994. In Situ localization of beet necrotic yellow vein virus (BNYVV) in rootlets of susceptible and resistant beet plants. Arch. Virol. 136: 349-361

Smith I.M., Dunez J., Lelliott R.A., Phillips D.H., Archer S.A., 1988. European Handbook of Plant Diseases. Black- well Scientific Publications, Oxford, England.

Tamada T., Baba T., 1973. Beet Necrotic Yellow Vein Virus from "Rhizomania" Affected Sugar Beet in Japan. Annls. Phytopath. Soc. Japan, 39: 325-352.

Tamada, T., 2016. General features of beet necrotic yellow vein virus. Rhizomania. 55-83.

TUIK, 2024. Türkiye İstatistik Kurumu. www.tuik.gov.tr. URL: https://biruni.tuik.gov.tr/medas/?kn=92&locale=tr (Erişim Tarihi:10.12.2024)

Assessment of Humic Acid Containing Fertilizer for Sustainable Crop Production: A Comprehensive Review

Segun OGUNMEFUN, Andon ANDONOV
Agricultural University Plovdiv, Bulgaria

***Corresponding Author**

Segun Ogunmefun
ogunmefunsegun2015@gmail.com

Abstract

The study is in the field of Regenerative Agriculture. The main task was the optimization of crop nutrition, especially silicon fertilization. The neglected element silicon (Si) turns out to be extremely necessary and useful for the development of crops, protects them from diseases and climate changes, suppresses toxic elements, and thus increase plant biomass accumulation, and yield. Field trials were conducted on two soils with contrasting soil properties with the application of mineral fertilizers - N, P, K, and Si. Each year, large amounts of silicon are irreversibly leached from the soil. A comparison of the amount of soil silicon determined at sowing and harvesting shows a depletion of this nutrient. Yield models were derived and optimum silicon levels were determined. It is recommended for soil and crop scientists to conduct extensive studies on the influence of silicon on different crops.

Keywords: Field experiment, Models, Silicon, Uptake, Yield

Introduction

As the global population continues to increase, it is becoming increasingly challenging to sustainably maintain agroecosystem output. In recent years, researchers have begun looking for healthier, pollutant-free food as a result of growing public awareness of food quality. However, addressing this challenge requires a collective global effort to enhance food production, reduce waste, and ensure equitable distribution, all while safeguarding the environment for future generations (Vioratti Telles de Moura et al., 2023).

In addition, numerous advancements have been made to enhance the quantity and quality of agricultural products. For instance, some organic fertilizers, like humic substances, have been partially or fully substituted for chemical fertilizers to increase nutritional values and reduce adverse environmental effects (Rai et al., 2021). Humic compounds, especially humic acids, have a wide range of ecological benefits and are economical and efficient ways to solve environmental issues and preserve the environment.

Humic acid is a dark, black substance, that is formed by microbial breakdown of plant and animal waste, and it is resistant to additional weathering (Dulaimy et al., 2020). It is a complex chemical naturally found in freshwater, soil, peat, and the ocean. Leonardite is a noteworthy source of humic acid (Dulaimy et al. 2020). Since humic acid's structure is made up of so many different components, it cannot be characterized by a single structural formula.

For sustainable crop production, the importance of humic acid compounds cannot be overvalued; they are vital components that are necessary for plants to be healthy. Plant growth physiological processes can be impacted by humic chemicals in both direct and indirect ways (Yang et al., 2014). Living things can benefit from humic chemicals for development, nourishment, biochemical process catalysis, and antioxidant activity (de Melo et al., 2016). According to Karakurt (2009), humic acid is an active ingredient in organic fertilizers and can be used as a substitute for traditional soil fertilization.

Numerous studies have been carried out worldwide to determine how humic acid affects various crop productions, but there isn't a systematic comparison of them. Furthermore, little information is known about the connections between humic acid, soil, and plant growth. Research evaluating the effects of varied humic acid concentrations on various crop species is still lacking. Thus, this review paper has described how humic acid in soils can sustainably increase crop production.

Characteristics of Humic Acid

Humic substances, composed of polymerized monomers, produce significant chemical byproducts like aromatic, phenolic, and aliphatic carboxylic acids. These compounds interact with metal ions, oxides, and hydroxides to break down soil minerals. Metal-humic combinations help plants obtain nutrients while avoiding leaching. Humic compounds also adsorb ammonium from urea and interact with clay minerals and humus. The cation exchange capacity of humic compounds varies due to the negative charge generated by proton release (Adani et al., 2006).

Benefits of Humic Acid

The following are some benefits associated with humic acid: 1) Adding organic matter to soils that lack it; 2) Improving nutrient uptake; and 3) Increasing the synthesis of chlorophyll. 3) Boost the vitality of the roots 5) Improved germination of seeds 6) Greater ability to retain fertilizer 7) Encourage the growth of beneficial microorganisms 8) Better yields and healthier plants.

According to Khaled et al. (2011), humic acids are helpful in releasing nutrients from the soil so that plants can use them when needed. According to Quillty (2011), the small size of humic acid molecules "allows them to reach the plant plasma membrane, where they effectively influence the assimilation of nutrients." Additionally, humic acid effectively collects harmful heavy metals (Sinha et al., 2011). Humic acid can improve the physical, chemical, and biological characteristics of soil as well as increase nutrient availability.

Impacts of Humic Acid on Soils

Humic acid as an organic substance is essential for improving soil properties, plant growth, and other agronomic aspects. In order to maintain the sustainability of agricultural output, humic acid-based products have been integrated into crop production in recent years. Humic acid has the ability to improve the physical, chemical, and biological characteristics of the soil as regards the studies that has been carried out. These characteristics include the soil's ability to retain water, cation exchange capacity (CEC), pH, carbon content, enzyme activity, macronutrient cycling, availability, and the aggregation and percentage of soil particles (Ampong et al. 2022). Numerous substances, such as macromolecules, hydrophobic and hydrophilic groups, and functional groups, are present in humic acid.

Humic acid's hydrophilic properties draw hydrogen ions, increasing the soil's ability to hold water. Humic acid, which is found in organic humus, has the capacity to significantly affect plant growth and soil health. Additionally, according to Fahramand et al. (2014) it enhances the structure and water-holding capacity of the soil as shown in Table1. While both addition and adsorption of humic acid to the soil contribute to increased aggregate stability, the adsorption approach produces more notable outcomes (Piccolo et al., 1996).

Increased cation exchange capacity is the result of humic acid's high surface area as a component of humus. The nutrients from organic fertilizer are therefore exchanged by humic acid, which then stores them in its molecule and releases them gradually as needed by plant.

Humic acid is the end product of the decomposition of plant matter. It has many binding sites for the macronutrients Ca, P, and K as well as the micronutrient Zn. Foliar spraying humic acid at 400 ppm in combination with NAA (naphthalene acetic acid) and vermicompost waste significantly increased the yield contributing character, plant growth indices, and chickpea yield (Kapase et al. 2014).

Impacts of Humic Acid on Sustainable Crop Production

Humic acid is a type of organic substance that can be utilized to enhance soil quality and increase plant uptake of nutrients and water. Consequently, there is a chance that this improvement will result in a reduction in the severity of the ailment. The chemicals may have a direct impact on plant diseases that are transmitted through soil in humic substances. According to in vitro research, the humic material inhibited the growth of Alternaria alternata, Fusarium culmorum, and Fusarium oxysporum species melons and lycopersici.

Humic acid has had a beneficial effect on germination in the medicinal plants Cichorium intybus and Borago officinalis. Humic acid levels 0, 15, and 30 g/L was studied, with the exception of germination percentage and mean germination time, the results showed that humic acid (30 g/L) strongly affected the plant's germination characteristics, including radical fresh weight, seedlings, and pedicle length (Ebrahimi and Miri 2016). Humic acid at all doses had a substantial impact on the grain yield of black cumin (Nigella sativa L.), with the control achieving the lowest rate (398.72 kg/ha) and the humic acid treatment achieving the highest rate (531.24

kg/ha). The grain output rose by 33.24% when the soil was treated with 3 kg/ha of humic acid (Aiyafar et al., 2015).

Furthermore, humic acid incorporation increases plant population by increasing the number of branches, a good indicator of appropriate rectangularity in plants (Table 1). The ideal planting geometry needs to be customized for a particular genotype in order to maximize the utilization of the few growth resources available and, consequently, stable yields (Arya et al., 2020). Its effects are also safe for the environment and reasonably priced (Alghabari, 2020).

Table 1. Impacts of humic acid doses on soil properties and growth of different crops

Soil properties/Crop	Humic acid dose	Observed result
Soil aggregates (Piccolo et al., 1996)	100–200 kg/ha	Stable soil aggregates are 40–120% higher than the control.
Soil water content (Piccolo et al. 1996)	0.05 g/kg	Compared to control, Acireale soil yielded a significantly higher field capacity (25.9%), permanent wilting point (21.7%), and available water content (29.9%).
Wheat (Arjumend et al., 2015)	150 mg/kg	Increased shoot length by 18%, root length by 29% and yield by 19–55% in comparison to the control.
Sugarcane (Sellamuthu and Govinda Swamy 2003)	20 kg/ha	Alkaline phosphate activity and catalase
Mustard (Rajpar et al., 2011)	6.35 kg/acre	Growth and yield increased
Fodder maize (Daur and Bakhashwain, 2013)	25 kg/ha	Increased fodder maize quality and growth
Chickpea (Kahraman, 2017)	9 kg/ha	Increased seed yield and the number of branches and pods per plant.
Tobacco (Rong et al., 2020)	14.8 kg/ha	Reduced the Pb, Cd, Zn, and Cu concentrations in comparison to the control by 39, 37%, 29%, and 18%, respectively.

The Way Ahead

A step toward sustainable agriculture may be represented by the application of humic acid. Fertilizer application has become a crucial procedure in modern agriculture. Humic acid can reduce the amount of fertilizer required, which subsequently makes the soil more fertile over time, even if it cannot replace fertilizer. Humic acid does not leave any trace in the soil or environment because it is a naturally occurring compound. It will, however, have a complementary effect on the crop that follows.

Finding the right method and the ideal humic acid dosage for a certain crop in a given area will be made easier with the help of this review article. Both the rhizosphere of the plants and the weather have an impact on productivity. We have power over the rhizosphere environment and can use the right techniques to alter it, even though we have no control over the climate. In this way, the risk of low production would decrease, and we might meet the desired yield while also contributing to the agriculture sector's economic growth.

Limitations

Among the limitations of humic acid is that it is less effective to apply a very high dose of humic acid (Liu et al., 2022). Although the positive effects of humic acids have been established, overuse of these substances may pollute the environment (Yigit et al., 2008). Humic acid treatment had little impact, and growth decline was even noted (Aydin et al., 2012). Numerous investigations have documented all experimental results, including positive, negative, and zero impacts (Lodhi et al., 2013).

Conclusion

In summary, this review has demonstrated that adding humic acid-containing fertilizer to soil has a positive impact on the majority of agricultural yield components. Applying humic acid can reduce the need for chemical fertilizers, which will in turn reduce pollution in the environment. Lastly, it can be said that the use of humic fertilizer not only boosts crop yields but also yields high-quality grains with high protein and carbohydrate content. It can have a big impact on reaching the worldwide objectives of sustainable agriculture.

References

Adani F., Sepagnol M. and Nierop K. G. J. 2006. Biochemical origin and refractory properties of humic acid extracted from maize plants. Biogeochemistry, 82(1): 55–65.

Aiyafar S., Poudineh H. M. and Forouzandeh M. 2015. Effect of humic acid on qualitative and quantitative characteristics and essential oil of black cumin under water deficit stress. DAV. International Journal Science, 4: 89-102.

Alghabari F. 2020. Evaluating mung bean performance under different types and rates of humic acid application in arid conditions of Saudi Arabia. International Journal of Agriculture and Biology, 24 (5): 1273-1278.

Ampong K, Thilakaranthna M. S. and Gorim L. Y. 2022. Understanding the role of humic acids on crop performance and soil health.

Arjumend, T., Abbasi M. K. and Rafique E. 2015. Effects of lignite-derived humic acid on some selected soil properties, growth, and nutrient uptake of wheat (Triticum aestivum L.) grown under greenhouse conditions. Pakistan Journal of Botany 47(6): 2231–38.

Arya A., Mahapatra S. S. and Singh V. K. 2020. Growth and yield attributing characteristics of chickpea varieties as influenced by altering plant rectangularity by varying plant spacing. International Journal of Chemical Studies 8(4): 3803–03.

Daur I. and Bakhashwain A. A. 2013. Effect of humic acid on growth and quality of maize fodder production. Pakistan Journal of Botany 45(S1): 21–25.

de Melo, B. A. G., Motta, F. L., & Santana, M. H. A. 2016. Humic acids: Structural properties and multiple functionalities for novel technological developments. Materials Science and Engineering: C, 62, 967–974. https://doi.org/10.1016/j.msec.2015.12.001

Dulaimy MA and El-Fahdawi WA. 2020. Effect of humic acid on growth and yield of barley humic acid as interacted with row spacing. Indian Journal of Ecology, 47: 62-65.

Ebrahimi M and Miri E. 2016. Effect of humic acid on seed germination and seedling growth of Borago officinalis and Cichorium intybus. Ecopersia 4(1): 1239–49.

Fahramand M, Moradi H, Noori M, Sobhkhizi A, Adibian M, Abdollahi S and Rigi K. 2014. Influence of humic acid on increased yield of plants and soil properties. International Journal of Farming and Allied Sciences 3(3): 339–41.

Hamideh D, Alvarez O. 2013. Sickle cell disease related mortality in the United States (1999–2009). Pediatric blood & cancer. 60(9):1482-1486.

Kahraman A. 2017. Effect of humic acid applications on the yield components in chickpea. Journal of Agricultural Faculty of Gaziosmanpasa University 34(1): 218–22.

Kapase P V, Deotale R D, Sawant P P, Sahane A N and Banginwar A D. 2014. Effect of foliar sprays of humic acid through vermicompost wash and NAA on morpho-physiological parameters, yield, and yield contributing parameters of chickpea. Journal of Soils and Crops. 24(1): 107–14.

Karakurt ,Y, Husnu Unlub, Halime Unlub and Huseyin Padem (2009). The influence of foliar and soil fertilization of humic acid on yield and quality of pepper. Acta Agriculturae Scandinavica, Section B - Soil & Plant Science 59(3):233-237.

Khaled H, Fawy H. A. 2011 Effect of different levels of Humic acids on the nutrient content, plant growth, and soil properties under conditions of salinity. Soil and Water Research. 1;6(1):21-9.

Liu Y, Schiff M, Dinesh-Kumar SP. Virus-induced gene silencing in tomato. The Plant Journal. 2022 Sep;31(6):777-86.

Lodhi S., Singhai A. K. 2013. Wound healing effect of flavonoid rich fraction and luteolin isolated from Martynia annua Linn. on streptozotocin induced diabetic rats. Asian Pacific journal of tropical medicine. 6(4):253-9.

Piccolo A., Pietramellara G. and Mbagwu J. S. C. 1996. Effects of coal-derived humic substances on water retention and structural stability of Mediterranean soils. Soil Use and Management 12(4): 209–13.

Quilty J. R., Cattle S. R. 2011. Use and understanding of organic amendments in Australian agriculture: a review. Soil Research. 49(1):1-26.

Rai, N., Rai, S. P., & Sarma, B. K. (2021). Prospects for Abiotic Stress Tolerance in Crops Utilizing Phyto- and Bio-Stimulants. Frontiers in Sustainable Food Systems, 5. https://doi.org/10.3389/fsufs.2021.754853

Rajpar I., Bhatti, M. B., Zia-ul-Hassan A. N. and Tunio S. D. 2011. Humic acid improves growth, yield, and oil content of Brassica compestris (L.). Pakistan Journal of Agriculture, Agricultural Engineering and Veterinary Sciences 27(2): 125–33.

Rong Q., Zhong K., Huang H., Li C., Zhang C. and Nong X. 2020. Humic acid reduces the available cadmium, copper, lead, and zinc in soil and their uptake by tobacco. Applied Sciences 10(3): 1077.

Sellamuthu K. M. and Govindaswamy M. 2003. Effect of fertilizer and humic acid on rhizosphere microorganisms and soil enzymes at an early stage of sugarcane growth. Sugar Technology 5(4): 273–77.

Vioratti Telles de Moura, O., Luiz Louro Berbara, R., França de Oliveira Torchia, D., Fernanda Oliveira Da Silva, H., Augusto van Tol de Castro, T., Carlos Huertas Tavares, O., Fernandes Rodrigues, N., Zonta, E., Azevedo Santos, L., & Calderín García, A. (2023). Humic foliar application as sustainable technology for improving the growth, yield, and abiotic stress protection of agricultural crops. A review. In Journal of the Saudi Society of Agricultural Sciences (Vol. 22, Issue 8, pp. 493–513). King Saud University. https://doi.org/10.1016/j.jssas.2023.05.001

Yang C. M., Wang M. H, Lu Y. F, Chang I. F., and Chou C. H. 2014. Humic substances affect the activity of chlorophyllase. J. Chem. Ecol. 30(5):1057-1065.

Yigit M.V., Mazumdar D., Lu Y. M. R. I. 2008. Detection of thrombin with aptamer functionalized superparamagnetic iron oxide nanoparticles. Bioconjugate chemistry. Feb 20;19(2):412-7.

Utilizing *Thiobacillus* bacteria for the reclamation of calcareous soils

Merve EKER *, Abdurrahman AY, Rıdvan KIZILKAYA

Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Türkiye

***Corresponding Author**

Merve EKER

merveeker1910@gmail.com

Abstract

Calcareous soils, characterized by high levels of calcium carbonate ($CaCO_3$), make up a significant portion of the world's soil. They are especially common in arid and semi-arid regions. Globally, these soils account for over 30% of the earth's surface. These soils tend to be alkaline, with a pH above 7, which makes it difficult for plants to absorb important nutrients like iron, phosphorus, and manganese. To improve the fertility of calcareous soils and make them better for farming, soil conditioners are needed. One common soil conditioner is adding elemental sulfur (S), which helps lower the soil's pH. However, the addition of elemental sulfur alone is not sufficient to change the soil pH. Thiobacillus bacteria is suitable for the existing soil and environmental conditions must be present in the environment. These bacteria are responsible for oxidizing sulfur compounds and converting sulfur into sulfuric acid. This acid reacts with calcium carbonate in the soil, turning it into calcium sulfate and releasing carbon dioxide. This process lowers the pH of the soil and makes nutrients more available for plants. By using sulfur and supporting the activity of Thiobacillus bacteria, calcareous soils can be improved for better plant growth.

Keywords: Calcareous soil, *Thiobacillus*, Soil pH, Soil contidioner, Sulfur oxidation

Introduction

Calcareous soils, prevalent in arid and semi-arid regions, constitute a substantial portion of the world's agricultural land, supporting approximately 60% of global food production (Gomiero, 2016). These soils are distinguished by their high pH, significant calcium carbonate content, and often poor organic matter levels, all of which impede the availability of essential nutrients such as phosphorus (P), zinc (Zn), and iron (Fe) (Havlin et al., 2014). Such nutrient limitations directly impact crop growth and yield, posing significant challenges for achieving sustainable agricultural productivity (Elgabaly, 1973; El-Hady and Abo-Sedera, 2006; FAO, 2016).

The improvement of calcareous soils has been a focus of soil management strategies aimed at ameliorating soil properties and enhancing nutrient bioavailability. One of the most effective approaches involves the application of elemental sulfur (S^0), a slow-releasing sulfur source that, upon oxidation, produces sulfate (SO_4^{2-}) and releases protons (H^+), thereby lowering soil pH. This transformation is catalyzed primarily by sulfur-oxidizing bacteria, such as Thiobacillus spp., which are crucial for converting S^0 into plant-available forms (Vidyalakshmi et al., 2009). However, the efficiency of sulfur oxidation is highly dependent on soil microbial activity, organic matter content, and environmental conditions, such as temperature and moisture (Gupta and Germida, 2021).

In recent years, organic amendments have gained attention for their role in complementing sulfur applications. Materials such as farmyard manure, poultry litter, and sugarcane filter cake not only supply organic carbon to stimulate microbial activity but also enhance sulfur oxidation by creating favorable conditions for sulfur-oxidizing microorganisms (Malik et al., 2021). Studies have shown that organic amendments, when combined with S^0, significantly improve microbial biomass, enzyme activities such as arylsulfatase and dehydrogenase, and overall nutrient cycling in calcareous soils (Tabak et al., 2020).

Microbial interactions play a central role in these processes. Heterotrophic microorganisms, in particular, contribute to sulfur oxidation by utilizing organic carbon as an energy source, while autotrophic sulfur oxidizers such as Thiobacillus spp. directly oxidize S^0 into sulfate (Chaudhary et al., 2023). The synergistic effects of organic amendments and elemental sulfur have been observed to not only enhance sulfur availability but also improve the bioavailability of key nutrients like phosphorus and micronutrients in calcareous soils (Vera et al., 2022; Ranadev et al., 2023).

Despite these advancements, the mechanisms underlying the combined application of elemental sulfur and organic amendments remain underexplored. There is a need for comprehensive studies that integrate the chemical, biological, and enzymatic dynamics of sulfur oxidation in calcareous soils. This study aims to address these gaps by evaluating the interactive effects of elemental sulfur, organic amendments, and microbial communities on the chemical and biological properties of calcareous soils. By synthesizing insights from recent literature, this work seeks to provide actionable recommendations for sustainable soil fertility management in calcareous systems.

Application of Elemental Sulfur in Calcareous Soils

- **Mechanisms of Sulfur Oxidation**

Elemental sulfur (S^0) is an effective amendment for calcareous soils, primarily due to its ability to undergo microbial oxidation, producing sulfuric acid (H_2SO_4) and releasing protons (H^+), which lower soil pH. This process enhances the solubility and bioavailability of essential nutrients such as phosphorus (P), zinc (Zn), and iron (Fe) (Vidyalakshmi et al., 2009). The oxidation of sulfur is predominantly mediated by sulfur-oxidizing bacteria, with Thiobacillus spp. playing a critical role. These autotrophic microorganisms utilize sulfur as an energy source, catalyzing its conversion to sulfate (SO_4^{2-}), the plant-available form of sulfur (Gupta and Germida, 2021).

Chemical oxidation of sulfur also occurs, although at a slower rate, and is influenced by soil pH, aeration, and moisture content. Studies have shown that the efficiency of sulfur oxidation can be enhanced in soils with adequate porosity and microbial populations (Chaudhary et al., 2023).

- **Role of Soil Properties in Sulfur Oxidation**

The oxidation of elemental sulfur is highly dependent on soil characteristics, including pH, calcium carbonate content, texture, and organic matter levels. In calcareous soils, the high buffering capacity due to calcium carbonate can slow down acidification, necessitating higher rates of sulfur application (Ranadev et al., 2023). Additionally, soil texture influences the diffusion of oxygen, a key requirement for microbial oxidation. Coarser-textured soils with better aeration generally exhibit faster sulfur oxidation than fine-textured soils (Malik et al., 2021).

Organic matter plays a pivotal role by serving as a substrate for heterotrophic microorganisms, indirectly supporting sulfur oxidation. Low organic matter levels in calcareous soils often limit microbial activity, which can be alleviated by the addition of organic amendments such as farmyard manure or poultry litter (Tabak et al., 2020).

- **Impacts on Nutrient Availability**

One of the most significant outcomes of sulfur oxidation in calcareous soils is the improved bioavailability of critical nutrients. Phosphorus availability, for instance, increases as acidification dissolves calcium phosphate compounds, converting them into forms that plants can absorb (Havlin et al., 2014). Similarly, micronutrients such as zinc and iron, which are typically immobile in alkaline soils, become more soluble and accessible to plant roots following pH reduction (Elgabaly, 1973).

Research by Malik et al. (2021) demonstrated that sulfur oxidation not only lowered pH but also enhanced the enzymatic activity of arylsulfatase, facilitating the mineralization of organic sulfur compounds. These processes collectively improve nutrient cycling, microbial activity, and overall soil fertility.

- **Synergistic Use with Organic Amendments**

The integration of elemental sulfur with organic amendments has shown to produce synergistic effects on soil fertility and microbial activity. Organic amendments such as farmyard manure, poultry litter, and sugarcane filter cake not only provide a carbon source for microbial communities but also improve soil structure and water retention, creating favorable conditions for sulfur oxidation (Tabak et al., 2020).

Studies have shown that poultry litter, due to its high organic carbon content and low C/N ratio, is particularly effective in accelerating sulfur oxidation and improving nutrient availability (Ranadev et al., 2023). Similarly, sugarcane filter cake has been reported to sustain microbial activity over longer periods, owing to its recalcitrant organic matter composition (Malik et al., 2021). The combined application of sulfur and organic matter also enhances the activity of sulfur-oxidizing bacteria such as Thiobacillus, boosting the efficiency of sulfur transformation and nutrient cycling (Vidyalakshmi et al., 2009).

Microbial Interactions and Enzymatic Activities in Sulfur Oxidation

- Role of Sulfur-Oxidizing Microorganisms

Microorganisms play a critical role in the oxidation of elemental sulfur (S^0), a key process for reducing soil pH and improving nutrient availability in calcareous soils. Among these, autotrophic sulfur-oxidizing bacteria such as Thiobacillus spp. are the primary agents of sulfur oxidation. These bacteria utilize elemental sulfur as an energy source, converting it into sulfate (SO_4^{2-}) and releasing protons (H^+) that lower soil pH (Vidyalakshmi et al., 2009).

In addition to autotrophs, heterotrophic microorganisms also contribute significantly to sulfur oxidation, albeit indirectly. By breaking down organic matter, they create a conducive environment for sulfur-oxidizing autotrophs by providing essential nutrients and enhancing soil structure (Chaudhary et al., 2023). Studies have shown that sulfur oxidation rates increase substantially when both autotrophic and heterotrophic microbial populations are active in the soil (Gupta and Germida, 2021).

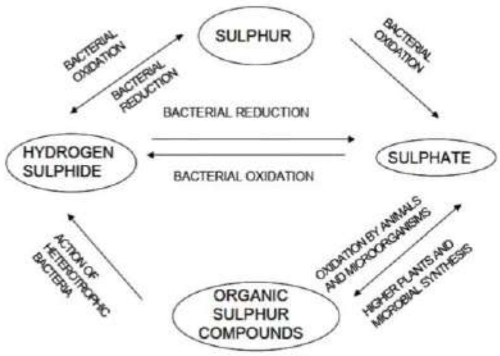


Figure 1. Oxidation process of sulphur (Vidyalakshmi et al. 2009)

- Enzymatic Contributions to Sulfur Cycling

Enzymes such as arylsulfatase and dehydrogenase are integral to the sulfur cycling process in soils. Arylsulfatase facilitates the mineralization of organic sulfur compounds, converting them into plant-available forms, while dehydrogenase is an indicator of overall microbial activity and organic matter decomposition (Malik et al., 2021).

Research indicates that the activity of these enzymes is significantly enhanced in the presence of organic amendments combined with elemental sulfur. For instance, arylsulfatase activity peaks during the middle stages of sulfur oxidation, coinciding with increased sulfate availability in the soil. This enzymatic activity has been positively correlated with microbial biomass and total organic carbon (Tabak et al., 2020). On the other hand, dehydrogenase activity is most pronounced in soils with easily degradable organic carbon, highlighting its reliance on organic matter inputs (Ranadev et al., 2023).

- Impact of Organic Amendments on Microbial Biomass

Organic amendments such as farmyard manure, poultry litter, and sugarcane filter cake have been shown to significantly enhance microbial biomass and activity. These materials provide essential nutrients and energy sources for soil microorganisms, promoting their proliferation and activity (Malik et al., 2021).

Poultry litter, for example, has a high organic carbon content and a low carbon-to-nitrogen (C/N) ratio, making it a readily available energy source for microbial communities. Similarly, sugarcane filter cake, with its recalcitrant organic matter composition, supports sustained microbial activity over longer periods (Tabak et al., 2020). The combined application of organic amendments and elemental sulfur results in a synergistic increase in microbial biomass, leading to improved sulfur oxidation and nutrient cycling (Chaudhary et al., 2023).

- Synergistic Effects of Microbial Communities

The interactions between different microbial communities, including autotrophic and heterotrophic microorganisms, create a synergistic effect that enhances sulfur oxidation and nutrient availability.

Autotrophic bacteria like Thiobacillus spp. directly oxidize sulfur into sulfate, while heterotrophic organisms decompose organic matter, releasing nutrients that further support autotrophic activity (Vidyalakshmi et al., 2009).

Studies have demonstrated that the diversity and functionality of microbial communities increase in soils treated with a combination of elemental sulfur and organic amendments. This microbial synergy not only accelerates sulfur oxidation but also improves the overall biological and chemical properties of the soil, making it more fertile and productive (Ranadev et al., 2023). Additionally, the presence of diverse microbial populations ensures resilience against environmental fluctuations, maintaining consistent sulfur transformation processes (Gupta and Germida, 2021).

Integration of Organic Amendments with Elemental Sulfur in Calcareous Soils

- Characteristics of Organic Amendments

Organic amendments such as farmyard manure, poultry litter, and sugarcane filter cake are widely used in agriculture for their ability to improve soil physical, chemical, and biological properties. Farmyard manure is rich in organic carbon and provides a balanced supply of nutrients, including nitrogen (N), phosphorus (P), and potassium (K), making it a versatile amendment for various soil types (Tabak et al., 2020). Poultry litter, with its low carbon-to-nitrogen (C/N) ratio and high nutrient content, is particularly effective in promoting microbial activity and nutrient cycling (Ranadev et al., 2023). Sugarcane filter cake, a byproduct of sugar production, is valued for its high organic matter content and recalcitrant organic compounds that support long-term microbial activity. These amendments also contain micronutrients such as zinc (Zn) and iron (Fe), which are essential for plant growth but often deficient in calcareous soils (Malik et al., 2021).

- Effects on Soil Chemical Properties

The addition of organic amendments has a profound impact on the chemical properties of calcareous soils. Organic matter increases the soil's cation exchange capacity (CEC), allowing it to retain more nutrients and improve their availability to plants (Gupta and Germida, 2021). Moreover, the decomposition of organic materials releases organic acids, which aid in dissolving calcium carbonate, further lowering soil pH and enhancing phosphorus solubility (Chaudhary et al., 2023). When combined with elemental sulfur, organic amendments amplify the acidification process, creating an optimal environment for nutrient availability. This synergy has been shown to significantly increase the bioavailability of phosphorus, zinc, and iron in calcareous soils, addressing common nutrient deficiencies (Havlin et al., 2014).

- Enhancement of Microbial Activity

Organic amendments are a critical source of energy and nutrients for soil microorganisms, directly influencing microbial biomass and activity. Farmyard manure and poultry litter provide easily degradable organic carbon, which supports the proliferation of heterotrophic microorganisms, indirectly boosting the efficiency of sulfur-oxidizing bacteria like Thiobacillus spp. (Vidyalakshmi et al., 2009). Sugarcane filter cake, with its high cellulose and lignin content, offers a slower but sustained release of nutrients, maintaining microbial activity over extended periods (Tabak et al., 2020). Research shows that soils treated with both elemental sulfur and organic amendments exhibit higher enzymatic activity, including arylsulfatase and dehydrogenase, which are key indicators of soil health and nutrient cycling (Malik et al., 2021).

- Long-Term Impacts on Soil Fertility

The long-term benefits of integrating organic amendments with elemental sulfur are particularly evident in the sustained improvement of soil fertility. Over time, these amendments contribute to the accumulation of organic carbon, enhancing soil structure, water retention, and resilience to environmental stressors (Ranadev et al., 2023). Additionally, the acidification induced by sulfur oxidation and organic acids creates a more favorable environment for root growth and nutrient uptake. Studies have demonstrated that this integrated approach not only improves short-term crop yields but also enhances the soil's capacity to support high productivity over multiple growing seasons (Gupta and Germida, 2021).

Synthesis of Findings and Implications

- Effects of Elemental Sulfur on Calcareous Soils

Elemental sulfur (S^0) has been identified as an effective soil amendment for improving the chemical properties of calcareous soils. Its oxidation, mediated by microbial activity, leads to the production of sulfuric acid, which lowers soil pH and dissolves insoluble calcium carbonate (Vidyalakshmi et al., 2009). This acidification process significantly enhances the availability of phosphorus (P), zinc (Zn), and iron (Fe), which are often deficient in calcareous soils (Havlin et al., 2014). Studies have shown that the application of sulfur can reduce soil pH by up to 1–2 units, depending on the rate and frequency of application, as well as soil texture and carbonate content (Ranadev et al., 2023). However, excessive sulfur applications can lead to undesirable effects, such as increased salinity and nutrient imbalances, underscoring the importance of precise application rates tailored to specific soil conditions (Malik et al., 2021).

- **Role of Organic Amendments in Soil Fertility**

Organic amendments, including farmyard manure, poultry litter, and sugarcane filter cake, play a crucial role in enhancing soil fertility, particularly when integrated with elemental sulfur. These materials improve soil organic matter content, enhance cation exchange capacity (CEC), and promote the retention and availability of nutrients (Tabak et al., 2020). In calcareous soils, the decomposition of organic matter releases organic acids that aid in dissolving calcium carbonate, further reducing soil pH and complementing the acidification effects of sulfur (Gupta and Germida, 2021). Additionally, organic amendments provide a steady supply of nutrients, such as nitrogen and potassium, and serve as a carbon source for microbial communities, thereby stimulating microbial biomass and activity (Chaudhary et al., 2023).

- **Microbial Contributions to Sulfur Oxidation**

Microbial communities, particularly sulfur-oxidizing bacteria like Thiobacillus spp., are central to the sulfur oxidation process. These bacteria convert elemental sulfur into sulfate (SO_4^{2-}), a plant-available form of sulfur, while releasing protons (H^+) that contribute to soil acidification (Vidyalakshmi et al., 2009). Heterotrophic microorganisms also play a supporting role by decomposing organic matter and providing essential nutrients and growth factors for sulfur-oxidizing bacteria (Malik et al., 2021). The combined activity of these microbial groups enhances sulfur oxidation rates, making the process more efficient in soils treated with both sulfur and organic amendments (Tabak et al., 2020). Enzymatic activities, such as those of arylsulfatase and dehydrogenase, further facilitate sulfur cycling by breaking down organic sulfur compounds and indicating overall soil microbial health. These activities are significantly enhanced in soils with adequate organic matter and active microbial populations (Ranadev et al., 2023).

- **Integrated Approaches for Sustainable Soil Management**

The integration of elemental sulfur and organic amendments offers a holistic approach to managing the challenges of calcareous soils. This combined strategy addresses multiple aspects of soil fertility, including pH reduction, nutrient bioavailability, and microbial activity enhancement (Gupta and Germida, 2021). Long-term studies have demonstrated that these integrated practices not only improve immediate crop yields but also contribute to the sustainability of agricultural systems by enhancing soil structure, water retention, and resilience to environmental stressors (Chaudhary et al., 2023). The synergistic effects of sulfur and organic amendments make them a cost-effective and environmentally friendly option for sustainable soil management in regions with calcareous soils (Malik et al., 2021). Practical applications of this approach include the development of tailored soil amendment programs that combine appropriate sulfur application rates with locally available organic materials. These practices can be further optimized through the use of microbial inoculants to enhance sulfur oxidation and nutrient cycling, ensuring long-term soil health and productivity (Ranadev et al., 2023).

Conclusion

This review demonstrates the significant potential of elemental sulfur and organic amendments in addressing the persistent challenges of calcareous soils. Elemental sulfur, through its microbial oxidation, effectively lowers soil pH and enhances the bioavailability of critical nutrients such as phosphorus, zinc, and iron. Organic amendments, including farmyard manure, poultry litter, and sugarcane filter cake, complement these effects by providing a carbon source for microbial activity, improving soil structure, and increasing water retention. Together, these practices create a synergistic system that enhances soil fertility and productivity while promoting sustainable soil management.

The practical applications of this integrated approach rely on precise sulfur application rates tailored to specific soil properties such as pH and calcium carbonate content, ensuring optimal acidification without causing over-acidification or salinity. Locally available organic materials, such as poultry litter and sugarcane filter cake, can serve as cost-effective solutions to enhance microbial activity and nutrient cycling. The incorporation of sulfur-oxidizing bacteria, such as Thiobacillus spp., further accelerates sulfur oxidation, making the process more efficient and sustainable. To maximize the benefits of these strategies, regular soil monitoring is essential for adapting management practices to changing conditions.

Despite these advancements, several research gaps remain. The long-term impacts of different organic amendments on soil health, structure, and microbial diversity require further exploration, especially in diverse cropping systems. The development of advanced microbial inoculants, including genetically modified or optimized strains, offers promising avenues to improve sulfur oxidation and nutrient availability. Furthermore, large-scale studies are needed to assess the effectiveness of these practices under varying climatic conditions, soil types, and agricultural systems. Alongside these scientific advancements, evaluating the environmental impacts, such as greenhouse gas emissions and potential nutrient leaching, is critical for ensuring the sustainability of these practices. Finally, cost-benefit analyses can guide the economic feasibility and adoption of these strategies by farmers.

In conclusion, the integration of elemental sulfur and organic amendments represents a sustainable solution for improving the fertility and productivity of calcareous soils. By addressing both chemical and biological limitations, these practices not only enhance crop yields but also contribute to long-term soil health and environmental sustainability. Future research and innovation will be vital for refining these methods and ensuring their applicability across diverse agricultural contexts.

Acknowledgments

This research was supported by Ondokuz Mayıs University under the project code BAP01-2024-5349. The authors thank all contributors for their valuable support.

References

Chaudhary, S., Sindhu, S.S., Dhanker, R., Kumari, A., 2023. Microbes-mediated sulphur cycling in soil: Impact on soil fertility, crop production and environmental sustainability. Microbiological Research 271, 127340. https://doi.org/10.1016/j.micres.2023.127340

Elgabaly, M.M., 1973. Reclamation and management of the calcareous soils of Egypt. In: FAO Soils Bulletin 21, Calcareous soils: report of the FAO/UNDP Regional Seminar on Reclamation and Management of Calcareous Soils, Cairo, Egypt, 27 Nov - 2 Dec 1972. FAO Soils Bulletin No. 21, pp. 123–127.

El-Hady, O.A., Abo-Sedera, S.A., 2006. Conditioning effect of composts and acrylamide hydrogels on a sandy calcareous soil. II-Physico-bio-chemical properties of the soil. Journal of Applied Sciences Research 2(11): 890-898

FAO, 2016. Management of Calcareous Soils Available at: https://www.fao.org/soils-portal/soil-management/management-of-some-problem-soils/calcareous-soils/zh/

Gomiero, T., 2016. Soil Degradation, Land Scarcity and Food Security: Reviewing a Complex Challenge. Sustainability 8(3), 281. https://doi.org/10.3390/su8030281

Gupta, V.V.S.R., Germida, J.J., 2021. Microbial transformations of sulfur in soil. In: Principles and Applications of Soil Microbiology. Gentry, T.J., Fuhrmann, J.J., Zuberer, D.A. (Eds.). Elsevier, pp. 489-522. https://doi.org/10.1016/B978-0-12-820202-9.00018-6

Havlin, J.L., Beaton, J.D., Tisdale, S.L., Nelson, W.L., 2014. Soil fertility and fertilizers: An introduction to nutrient management Pearson. 528p.

Malik, K.M., Khan, K.S., Billah, M., Akhtar, M.S., Rukh, S., Alam, S., Munir, A., Mahmood Aulakh, A., Rahim, M., Qaisrani, M.M., Khan, N., 2021. Organic Amendments and Elemental Sulfur Stimulate Microbial Biomass and Sulfur Oxidation in Alkaline Subtropical Soils. Agronomy 11(12), 2514. https://doi.org/10.3390/agronomy11122514

Ranadev, R., Revanna, A., Bagyaraj, D.J., Shinde, A.H., 2023. Sulfur oxidizing bacteria in agro ecosystem and its role in plant productivity—a review, Journal of Applied Microbiology 134 (8), lxad161. https://doi.org/10.1093/jambio/lxad161

Tabak, M., Lisowska, A., Filipek-Mazur, B., Antonkiewicz, J., 2020. The Effect of Amending Soil with Waste Elemental Sulfur on the Availability of Selected Macroelements and Heavy Metals. Processes 8(10), 1245. https://doi.org/10.3390/pr8101245

Vera, M., Schippers, A., Hedrich, S., Sand, W., 2022. Progress in bioleaching: fundamentals and mechanisms of microbial metal sulfide oxidation – part A. Applied Microbiology and Biotechnology 106, 6933–6952. https://doi.org/10.1007/s00253-022-12168-7

Vidyalakshmi, R., Paranthaman, R., Bhakyaraj, R., 2009. Sulphur oxidizing bacteria and pulse nutrition—a review. World Journal of Agricultural Sciences 5(3):270–278

Effects of land use types on soil aggregate stability

Betül Selin PACCI *, Coskun GULSER, Orhan DENGIZ
Ondokuz Mayıs University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Samsun, Turkey

***Corresponding Author**

Betül Selin Pacci
betulpaccii@outlook.com

Abstract

Aggregate stability is known as a main factor improving agronomic productivity, controlling topsoil hydrology, crust ability and erodibility. In this study, we aimed to determine the organic matter (OM) content and aggregate stability (AS) values of soils under different land use types. The soil organic matter contents were determined for cultivated fields between 0,53% and 3,28%, for forest areas between 0,90% and 4,41%, and for pasture fields between 0,23% and 3,19%. The mean values of OM contents for different land use types were ordered as follows; cultivated fields (1,84%) < pasture fields (2,29%) < forest areas (2,63%). The water stable aggregate values were determined for cultivated fields between 32,78% and 84,74%, for forest areas between 15,55% and 80,86%, and for pasture fields between 36,08% and 78,31%. The mean values of AS for different land use types were ordered as follows; cultivated fields (55,85%) < forest areas (59,03%) < pasture fields (59,28%). While there were significant relationships between soil OM content and AS values in forest areas (r = 0,534**) and pasture fields (r = 0,738**), there was not a significant relation between OM content and AS values in cultivated fields (r = 0,016). It was found that increasing soil OM content in forest and pasture fields caused increases in AS values. Soil cultivation decrease in soil OM content and also decrease AS values with dispersing soil structure. As a conclusion, land use type has effects on soil OM accumulation and soil structural parameters, and uncultivated areas such as forest and pasture have better physical conditions compared with cultivated fields.

Keywords: Soil structure, organic matter, forest, pasture, soil cultivation

Introduction

Soil aggregate stability is one of the key characteristics of soil structure, determining its resistance to water and wind erosion. Soil aggregates are larger structures formed by the combination of soil particles with water and organic matter, which increase the structural integrity of the soil and its resistance to erosion. Land use is one of the most important factors influencing soil aggregate stability. Agriculture can negatively affect soil aggregate stability due to various tillage practices performed on the soil. Frequent tillage, in particular, damages the soil structure and leads to a loss of organic matter, which causes the aggregates to collapse (Alaboz, 2017). This study aims to examine the effects of different land uses on soil aggregate stability. In agricultural areas, practices such as excessive tillage and monoculture farming can have negative impacts on soil aggregate stability. Agricultural practices disrupt the physical structure of the soil, decrease organic matter content, and lead to the collapse of soil aggregates. Continuous tillage, in particular, leads to the degradation of soil aggregates (Borrelli et al., 2020).

Rangeland areas can enhance soil aggregate stability by maintaining the sustainability of natural vegetation. However, in livestock grazing, excessive grazing and damage to the vegetation can lead to the collapse of soil aggregates. On the other hand, controlled grazing and proper rangeland management can maintain soil organic matter content, stabilizing soil aggregates. It has been shown that rangelands, with the help of plant roots, have a high capacity to bind soil and produce stronger soil aggregates (Liao et al., 2019). Reducing grazing intensity and frequency is another important factor that improves soil structure.

Forest areas have the highest potential for maintaining soil aggregate stability among land use types. Forests create a thick organic layer that protects the soil surface, and these organic materials play a significant role in binding soil aggregates. In forest ecosystems, preserving soil structure allows water to remain on the soil surface for longer, reducing the risk of erosion (Borrelli et al., 2019). Additionally, forest roots contribute to the soil structure, helping aggregates become more stable.

While the effects of land use types on soil aggregate stability differ between agricultural, rangeland, and forest areas, it is possible to make these land uses resistant to these effects through specific management strategies. Forest areas, as ecosystems that naturally protect soil aggregates, are at the top of the list, while agricultural areas generally have the lowest stability. However, correct agricultural practices, such as organic fertilization, minimum tillage, and cover crops, can improve soil aggregate stability (Gülser, 2018).

Material and Methods

Study area, Soil Sampling and Dataset

The Aşağı Aksu basin is located within the borders of Samsun province in the Central Black Sea Region of Turkey. Geographically, Samsun is situated between 41° 17′ 25″ North latitude and 36° 20′ 1″ East longitude. To the west, it borders Sinop; to the southwest, it borders Çorum; to the south, it borders Amasya; to the southeast, it borders Tokat; and to the east, it borders Ordu. With an area of 9,725 km^2, it represents 1.25% of Turkey's total land area. The research area (Figure 1) is situated at altitudes ranging from 140 m to 510 m above sea level. The northern part of the area has a high slope, while the southern part consists mostly of moderate and low slopes, with some areas of high slope. Due to its predominantly mountainous and forested nature, a significant portion of the province's vegetation is composed of trees, while forest cover is almost nonexistent in the lowland areas. The research area covers approximately 486.1 hectares and is located between 36°10'54.48" - 36°09'08.91" East longitude and 41°21'31.37" - 41°20'26.80" North latitude.

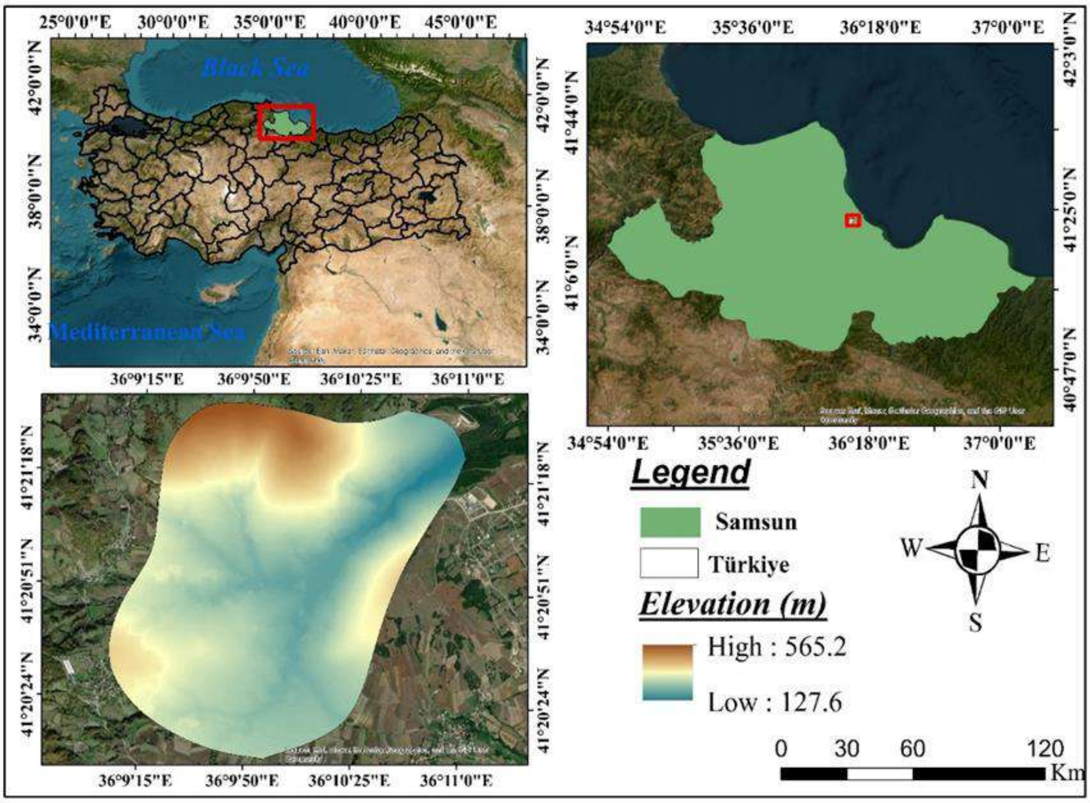


Figure 1. Location map of the Study Area

In remote sensing studies, there are various methods of accuracy analysis. In the classification performed for the study area, land use types were identified as Agricultural Land, Forest, Rangeland, Barren Land, Lake, and Non-Agricultural Areas. As shown in Figure 2, the majority of the study area is forest land, followed by agricultural land, rangeland, barren land, lake, and residential areas in sequence.

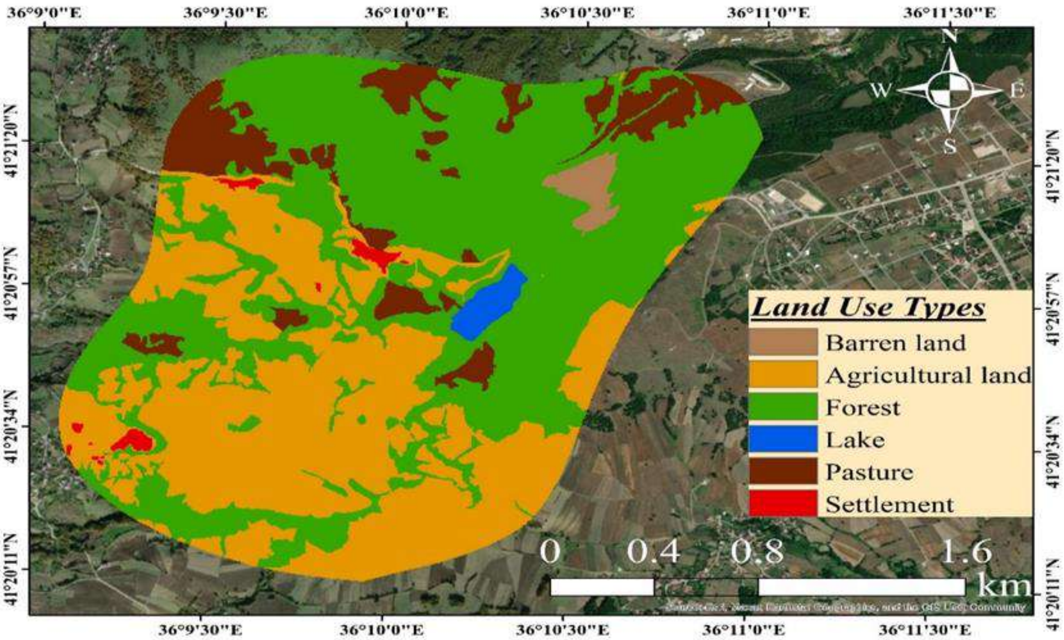


Figure 2. Land use-land cover map of the study area

A total of 54 surface soil samples were collected from different land use types within the watershed cultivated land, forest land, and pasture land identified and distributed using Google Earth (Figure 3). The soil samples were analyzed for texture (Bouyoucos, 1962), bulk density (Blake and Hartge, 1986), organic matter content (Jackson, 1958), soil pH (McLean, 1982), electrical conductivity (EC) using a glass electrode (Rhoades, 1993), and lime ($CaCO_3$) content using the Scheibler calcimeter (Anonymous, 1992).

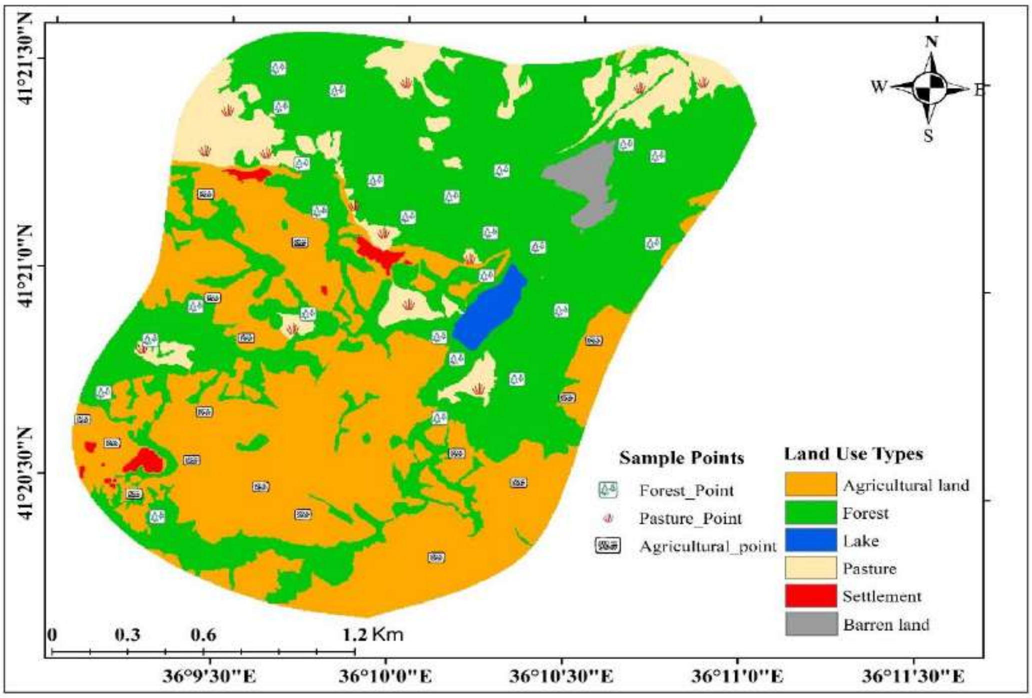


Figure 3. Sample points taken from the study area

Results And Discussion

The organic matter content is highly variable in the three selected land uses. This study revealed the effects of different land use types on soil organic matter content and aggregate stability. The results showed that forest and pasture areas have higher organic matter content and aggregate stability compared to agricultural lands (Figure 4). In particular, a strong and significant relationship was found between soil organic matter content and aggregate stability in forest and pasture areas, confirming that organic matter accumulation improves soil structure and enhances erosion resistance. In agricultural lands, however, aggregate stability was found to be lower due to continuous soil tillage and organic matter loss. It was determined that agricultural practices degrade soil structure, reducing aggregate stability and making the soil more vulnerable to erosion.

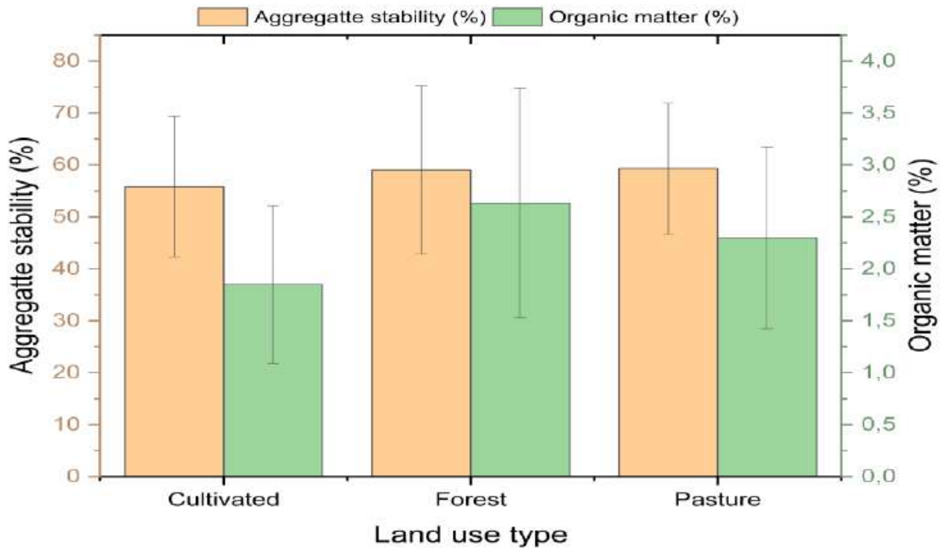


Figure 4. Changes of organic matter and aggregate stability on different land use types.

Forest and pasture areas provide more suitable conditions for maintaining soil health and reducing erosion risk, while in agricultural lands, soil structure can be improved through proper management strategies such as minimum tillage, organic fertilization, and cover crops. These findings help us understand the effects of different land use types on soil properties and provide an important basis for sustainable land management.

Aggregate stability is crucial for soil quality as it ensures the arrangement, stability, size of pores, and their continuity within the soil (Altıkat and Çelik, 2009). Aggregate stability is a function of the cohesive forces between soil particles, resisting the dispersive forces that separate them. These cohesive forces between soil particles are influenced by silica clays, carbonates, and organic compounds (Kemper and Rosenau, 1986). Soil organic matter (SOM) is one of the primary determinants of soil aggregate stability, enhancing the resilience of soil particles against water by keeping them bound together. Organic matter strengthens the stability of aggregates by binding soil particles through components such as humus, polysaccharides, and microbial exudates. Continuous applications of organic matter promote the formation of large macro-aggregates, thereby making soil structure more resilient. These processes slow water runoff on the soil surface, preventing erosion and increasing soil fertility (Tisdall and Oades, 1982; Six et al., 2004; Bronick and Lal, 2005; Saygın F et al., 2024).

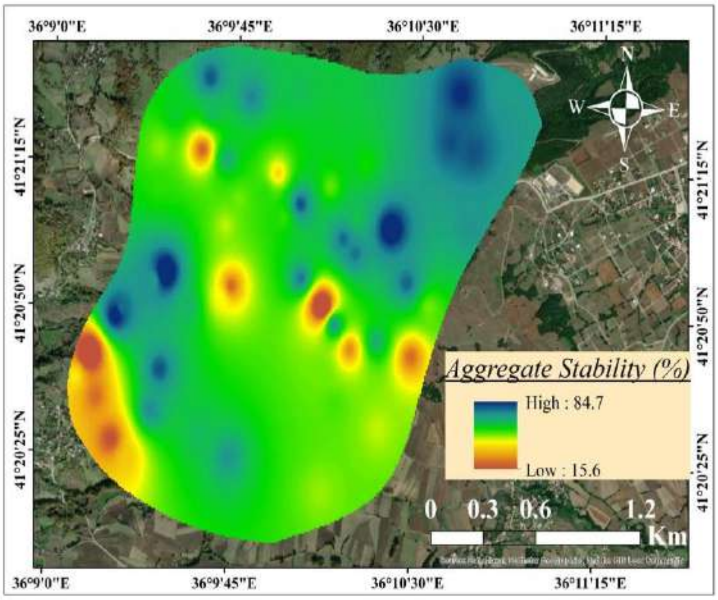


Figure 5. Aggregate stability distribution map of the study area

When examining the aggregate stability distribution map of the study area (Figure 5), it is observed that a significant portion of the area exhibits high to moderate aggregate stability. This result is further corroborated by the organic matter distribution map, which demonstrates a parallel relationship across much of the area (Figure 6). However, in the southeastern part of the area, no such parallelism is observed between organic matter and aggregate stability distributions. This discrepancy is thought to be due to agricultural practices such as soil tillage and organic matter addition in farmlands.

Research indicates that agricultural practices like soil tillage and organic matter application have significant effects on soil organic matter content and aggregate stability. Soil tillage increases soil aeration, which accelerates the decomposition of organic matter and consequently reduces organic matter content. This can lead to the deterioration of soil structure and a decrease in aggregate stability (Özdemir and Kop Durmuş, 2016).

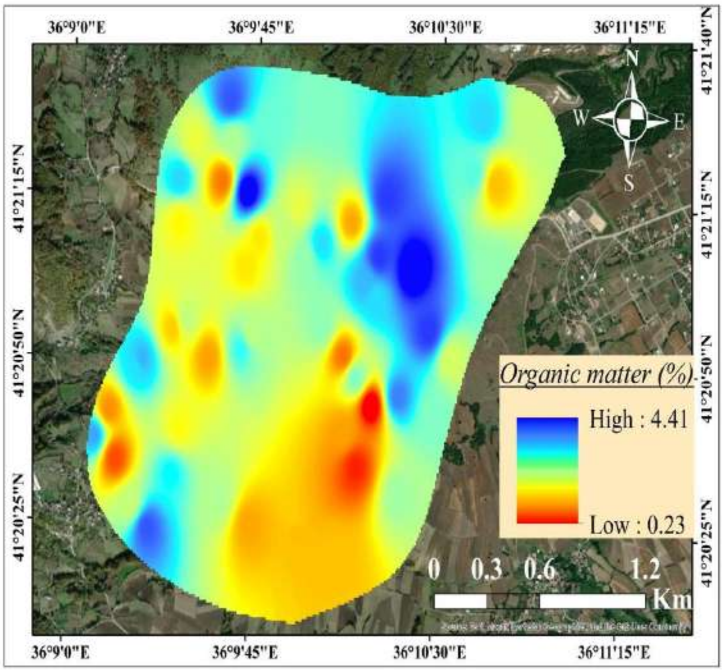


Figure 5. Organic matter distribution map of the study area

Conclusion

This study has demonstrated that different land-use types have significant effects on soil organic matter accumulation and soil structural parameters. The results reveal that areas such as forests and pastures, where no soil tillage is performed, have better physical soil conditions compared to agricultural lands subjected to soil tillage and agricultural practices. These findings provide crucial insights into the impact of land use on soil quality and are expected to guide future research aimed at evaluating and improving different land-use practices.

Acknowledgments

This research was supported by Ondokuz Mayıs University under the project code PYO.ZRT.1914.23.002. The authors thank all contributors for their valuable support.

References

Altıkat, S., & Çelik, A. (2009). Toprak Đsleme Sistemlerinin Önemli Bazı Toprak Kalite Kriterlerine Olan Etkileri. Alinteri Journal of Agriculture Science, 16(1), 33-41.

Atanassova, I., Petkova, Z., Sadovski, A., 2022. Silicium – the element of plant and human health. Ecological Engineering and Environment Protection, No 3-4, p. 5-15. (Bg).

Aydın, H., Kızılkaya, R., Ay, A., 2022. Importance of silicon in agriculture. International Symposium on "Soil Science and Plant Nutrition". 2-3 December 2022, Samsun, Turkey. Book of Proceedings, pp. 254-258.

Barao, L., 2022. The Use of Si-Based Fertilization to Improve Agricultural Performance – Review. Journal of Soil Science and Plant Nutrition 23: 1096–1108. https://doi.org/10.1007/s42729-022-01106-1

Bocharnikova, E.A., Matichenkov, V.V., 2012. Influence of plant associations on the silicon cycle in the soil-plant system. Applied Ecology and Environmental Research, 10 (4): 547-560. http://dx.doi.org/10.15666/aeer/1004_547560.

Bronick, C. J., & Lal, R. (2005). Soil structure and management: a review. Geoderma, 124(1-2), 3-22.

EPRS, 2016. European Parliament, Directorate-General for Parliamentary Research Services, Daheim, C., Poppe, K., Schrijver, R., Precision agriculture and the future of farming in Europe – Scientific foresight study, European Parliament, 2016. Available at: https://data.europa.eu/doi/10.2861/020809

FAO, 2015. World Reference Base for Soil Resources, 2014. FAO, Rome, Italy. 203. Available at: http://www.fao.org/3/i3794en/I3794en.pdf

Giller, K. E., Hijbeek, R., Andersson, J. A., Sumberg, J., 2021. Regenerative Agriculture: An agronomic perspective. Outlook on Agriculture, 50(1), 13–25. https://doi.org/10.1177/0030727021998063

Heckman, J.R., Wolf, A., 2009. Recommended Soil Tests for Silicon. Cooperative Bulletin. Northeastern Regional Publication No. 493, 3rd Edition.

Hou, L, Ji, S., Zhang, Y., Wu, X., Zhang, L, Liu, P., 2023. The mechanism of silicon on alleviating cadmium toxicity in plants: A review. Frontiers in Plant Science 14: 1141138. https://doi.org/10.3389/fpls.2023.1141138

Kemper, W. D., & Rosenau, R. C. (1986). Aggregate stability and size distribution. Methods of soil analysis: Part 1 Physical and mineralogical methods, 5, 425-442.

Korndörfer, G.H., Lepsch, I., 2001. Effect of silicon on plant growth and crop yield. In: Datnoff L.E., G.H. Snyder, G.H. Korndörfer, R. (Eds.). Silicon in Agriculture. Elsevier, p. 133-147. https://doi.org/10.1016/S0928-3420(01)80011-2

Meena, V. D., M. L. Dotaniya, V. Coumar, S. Rajendiran, Ajay, S. Kundu, A. Subba Rao. 2014. A Case for Silicon Fertilization to Improve Crop Yields in Tropical Soils – Review. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences 84(3):505–518. https://doi.org/10.1007/s40011-013-0270-y

Özdemir, N., & Durmuş, Ö. T. K. (2016). Organik düzenleyicilerin asit, nötr ve alkalin toprakların agregat stabilitesi üzerine etkileri. Toprak Bilimi ve Bitki Besleme Dergisi, 4(1), 22-26.

Pavlovic, J., Kostic, L., Bosnic, P., Kirkby, E.A & Nikolic, M. 2021. Interactions of silicon with essential and beneficial elements in plants. Frontiers in Plant Science, 12, 1224. https://doi.org/10.3389%2Ffpls.2021.697592

Sadovski, A. 2020. An Introduction to Mathematical Agronomy: Theoretical and Experimental Bases. LAP Lambert Academic Publishing. ISBN 978-620-2-51889-5, 284 pp.

Sadovski, A. 2021. Determination and use of the soil equivalent in fertilizer experiments. Rastenievadni nauki, 58(1) 62-67.

Saygın, F., Dengiz, O., & Pacci, S. (2024). Mera Arazilerinde Yer Alan Toprakların SMAF Modeli Yardımıyla Toprak Kalite Durumlarının Değerlendirilmesi (Ulaş-Acıyurt Örneği). Turkish Journal of Agricultural and Natural Sciences, 11(3), 849-859.

Snyder, G.H. 2001. Methods for silicon analysis in plants, soils, and fertilizers. In: Datnoff L.E., G.H. Snyder, G.H. Korndбrfer (Eds.). Silicon in Agriculture. Elsevier, p. 185-196. https://doi.org/10.1016/S0928-3420(01)80015-X.

Tisdall, J. M., & OADES, J. M. (1982). Organic matter and water-stable aggregates in soils. Journal of soil science, 33(2), 141-163.

Zargar, S.M., Mahajan, R., Bhat, J.A., Nazir, M., Deshmukh, R. 2019. Role of silicon in plant stress tolerance: Opportunities to achieve a sustainable cropping system. 3 Biotech 9, 73. https://doi.org/10.1007/s13205-019-1613-z

Zuchuan, L., Zhaoliang, S., Zhifeng, Y., Qian, H., Alin, S., Linan, L., Xiaomin, Y., Shaopan, X., Yongchao, L. 2018. Silicon enhancement of estimated plant biomass carbon accumulation under abiotic and biotic stresses. A meta-analysis. Agronomy for Sustainable Development, 38, 26. https://doi.org/10.1007/s13593-018-0496-4

International Symposium on "Soil Science and Plant Nutrition"
Federation of Eurasian Soil Science Societies cooperation with Erasmus Mundus Joint Master Degree in Soil Science Programme
13 - 14 December 2024 / Samsun, Türkiye
With the support of the Erasmus+ Programme of the European Union

The determination of fungal flora into their rhizosphere and root of some wild grasses from different elevation levels of Türkiye

Ahmet KANDEMİR [1], Bayram KANSU [2,*], Berna TUNALI [1]

[1] Ondokuz Mayıs University, Faculty of Agriculture, Plant Protection, Samsun, Türkiye

[2] Ondokuz Mayıs University, Samsun Vocational School, Animal and Plant Protection Department, Samsun, Türkiye

***Corresponding Author**

Bayram KANSU

bayramkansu@omu.edu.tr

Abstract

Poaceae communities have large spread areas such as agricultural, aquatic, or arid habitats worldwide. These plants which survive considerably various ecology and soil conditions, can resist abiotic and biotic stress conditions. Türkiye has a convenient territorial area that includes plains and plateaus from zero to five-thousand elevation for the evolution of wild grass species such as emmer wheat or several important Aegilops. This study aimed to identify and determine the fungal species within potential pathogenic, endophytic, or saprophytic from their rhizosphere and roots of six wild grasses obtained from three different elevation levels of Türkiye. A total of forty wild grass samples including Lolium, Festuca, Avena, Seceale, Aegilops, and Bromus genera were collected into the thirty-two pasture areas and nearly to agricultural fields. Two separate replicants obtained from the rhizosphere and root of each plant sample were placed onto the pentachloronitrobenzene agar medium and incubated at 25 oC in darkness condition for five days after surface sterilization of the plant tissues with 1% hypochlorite solution and washing at double distilled water twice. After incubation, the mycelial growth was identified by morphological characteristics on a light microscopy, and the fungal genus and species were accounted for by wild grasses hosts and elevation levels. As a result of this study, a total of one hundred thirty-one fungal isolates were recovered from the rhizosphere and roots with ninety-three and thirty-eight, respectively. Fusarium culmorum, Rhizoctonia, Bipolaris sorokiniana, Pythium-like, and Gaeumannomyces genera and species were obtained from plant tissues as known as soil-borne pathogens. The highest range of fungal isolates was found at than 1600 meters elevation levels in roots and the rhizosphere with 44% and 35.9%. Consequently, there can be various in the range of fungal density and diversity depending on the elevation level, and out of the Lolium and Avena, many of these can be able to resist particularly soil-borne pathogens.

Keywords: Altitude, Fungal diversity, Poaceae, Soil borne, Türkiye, Wild grass

Introduction

Poaceae communities have large spread areas such as agricultural, aquatic, or arid habitats worldwide. These plants which survive considerably various ecology and soil conditions, can resist abiotic and biotic stress conditions. At the same time, the reports from various countries that grasses can have a role in the epidemiology of diseases caused by many of the pathogens (Crofts et al. 1988; Burgess et al. 2001). The plant diseases that caused by fungal species, particularly soilborne fungi, is one of the most destructive for plant productivity and quality. Gibson (2009) suggested that the pathogenic fungi significantly affected the population biology of grasses and their contribution to plant communities by affecting the physiology and chemical composition of those grasses. In the other hand, the fact that hospitality of the grasses for many pathogenic fungi is an important issue in terms of the life cycle of the diseases that restrict to agricultural production.

Türkiye has a convenient territorial area that includes plains and plateaus from zero to five-thousand elevation for the evolution of wild grass species such as emmer wheat or several important Aegilops. The Fertile Crescent, parts of southern Turkey, is one of the world's main centers of wild relatives of wheat (Davis, 1985; Cabi et al. 2010).

This study aimed to identify and determine the fungal species within potential pathogenic, endophytic, or saprophytic from their rhizosphere and roots of six wild grasses obtained from three different elevation levels of Türkiye.

Material and Methods

Plant materials and surveys

Wild grasses plants were randomly collected from fourteen provinces of central, east- western and northern Anatolia regions of Türkiye in 2019 summer seasons. Also, the plant samples were grouped as a three altitudes levels of depends on their locations (Figure 1.). Reaches maturity, the plants, at 20 km from the selected routes, each one emphasizing a randomly collected wild grains encountered in the road to the right and left of 10 to 15 plants collected, numbered, brought the laboratory were placed in envelopes. By the end of July 2019, besides wild cereals were taken by chance and brought to the laboratory. Herbariums separated from the plant samples for diagnosis, root and rhizosphere parts of these grasses to put in envelopes and stored on the shelves of the refrigerator until tested to infection. On the other hand, wild grasses were identified according to the (Davis, 1968) diagnostic criteria.

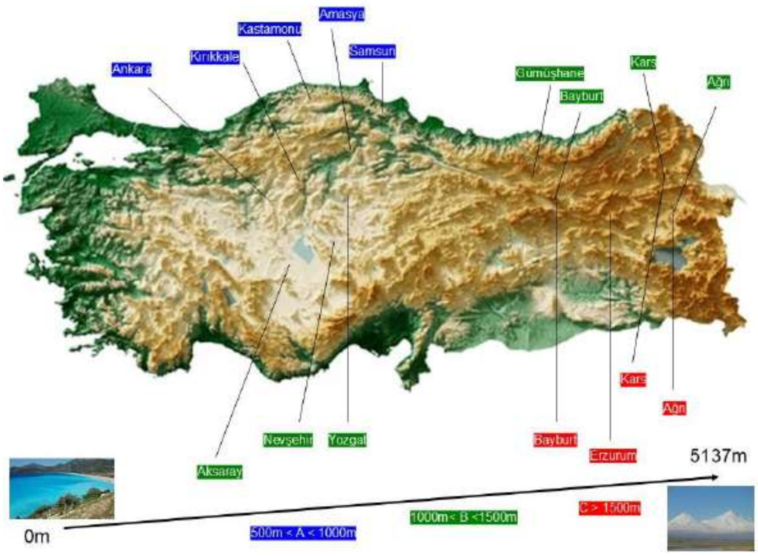


Figure 1. The locations of wild grasses that collected areas on their altitude levels

Fungal isolations

Two pieces of crown and rhizosphere parts randomly selected from two plants were surface sterilized by soaking for 3 minutes in sodium hypochlorite (1 % active chloride) and then rinsed twice in sterile distilled water and placed on tissue paper for 5-10 minutes for dried in a laminar flow cabinet. Then, these parts were plated on potato dextrose agar (PDA, Sigma,) medium and used two replicates those were incubated under 24◦ C, 12 h NUV+day light/12 h dark conditions, into an incubator for a period of week. Fusaria colonies were carried out on synthetic nutrient agar (SNA) medium for identification while the other colonial growth transferred onto the PDA.

Morphological identification

The diagnoses are made under the stereo microscopy and light microscopy some of the fungi of the genus-level diagnostics. Identification at the species level was carried out according to the diagnostic criteria found principally in publications by Barnett and Hunter (1998) for spore formed fungi, and Gerlach and Nirenberg, (1982) and Leslie and Summerall, (2006) for particularly Fusarium.

Data Analysis

The SPSS v21 statistical packages (IMB, Statistic, OMU Licensed for online users) were used analysis of differences between the variances by One-Way ANOVA. The variance homogeneity was analysis Levene Test (Levene, 1960) and means were grouped by Duncan multiple range test (Duncan, 1955). The means of isolation rate (%) according to number of fungal isolates on fungal species, wild grasses hosts and altitude levels were assessed.

Results And Discussion

A total of forty wild grass samples including Lolium, Festuca, Avena, Seceale, Aegilops, and Bromus genera were collected into the thirty-two pasture areas and nearly to agricultural fields in sixteen provinces of Türkiye. The number of fungal isolates were ninety-three and thirty-nine from rhizosphere and roots, respectively (Table 1).

Table 1. The number of fungal isolates on different locations, altitudes and wild grasses

Wild Grasses	Altitude	Host Plant	Number of Fungus	
Provinces/Towns	(meters)	Genera/Species	Rhizosphere	Root
Kastamonu/Tosya	476	*Festuca* sp.	2	1
Bayburt/Demirözü	1652	*Lolium perenne*	2	1
Ağrı/Merkez	1717	*Avena fatua*	5	2
Ankara/Merkez	1003	*Seceale cereale*	4	0
Bayburt/Merkez	1649	*Lolium perenne*	0	0
Yozgat/Sorgun	1187	*Seceale cereale*	4	1
Bayburt/Demirözü	1652	*Festuca* sp.	2	1
Kars/Digor	1656	*Seceale cereale*	3	0
Kars/Merkez	2013	*Lolium perenne*	2	0
Kars/Merkez	2013	*Avena fatua*	0	0
Kars/Digor	1530	*Avena fatua*	2	0
Bayburt/Demirözü	1652	*Bromus squarrosus*	3	1
Ankara/Merkez	1003	*Avena fatua*	1	1
Nevşehir/Merkez	1354	*Avena fatua*	2	1
Ankara/Merkez	1003	*Aegilops* sp.	2	2
Ankara/Kalecik	794	*Seceale cereale*	1	0
Samsun/Havza	722	*Avena fatua*	1	0
Gümüşhane/Kelkit	1374	*Festuca* sp.	1	1
Samsun/Havza	722	*Lolium perenne*	3	0
Kırıkkale/Karakeçili	860	*Avena fatua*	4	3
Gümüşhane/Kelkit	1374	*Lolium perenne*	2	1
Kars/Digor	1530	*Lolium perenne*	2	1
Yozgat/Boğazlıyan	1127	*Aegilops* sp.	2	2
Amasya/Gümüşhacıköy	890	*Lolium perenne*	2	1
Erzurum/Aşkale	1640	*Avena fatua*	2	1
Ağrı/Tutak	1563	*Lolium perenne*	4	2
Ağrı/Merkez	1726	*Festuca* sp.	2	0
Ağrı/Tutak	1860	*Lolium perenne*	2	1
Bayburt/Merkez	1548	*Festuca* sp.	2	2
Kars/Digor	959	*Festuca* sp.	2	2
Ağrı/Merkez	1726	*Lolium perenne*	2	1
Erzurum/Aziziye	1762	*Lolium perenne*	2	2
Erzurum/Pasinler	1652	*Lolium perenne*	2	0
Ağrı/Doğubeyazıt	1647	*Lolium perenne*	2	0
Aksaray/Ortaköy	1153	*Aegilops* sp.	5	3
Ağrı/Diyadin	1882	*Lolium perenne*	2	1
Bayburt/Merkez	1649	*Avena fatua*	6	2
Yozgat/Sarıkaya	1173	*Lolium perenne*	2	0
Gümüşhane/Köse	1514	*Festuca* sp.	2	1
Erzurum/Pasinler	1760	*Lolium perenne*	2	1
			93	39

* Blue column: <1000m, Dark Green: between 1000 and 1500m, Red: >1500m

A total of one hundred thirty-one fungal isolates, belong to twenty-one different fungal genera, were recovered from the rhizosphere and roots. A bacterial colony was only obtained from agar medium while 9.7% of sterile fungal growth that include only hypha and non-produce's fungal reproductive structure, such as conidium or chlamydospores. The eleven fungal genera were not detected on roots parts of the plants. The highest fungal ratio was in Penicillium, Sterile fungi and Aspergillus on rhizosphere while Penicillium, Aspergillus and Torula were in roots (Table 2). Fusarium culmorum, Rhizoctonia, Bipolaris sorokiniana, Pythium-like, and

Gaeumannomyces genera and species were obtained from plant tissues as known as soil-borne pathogens on grasses and cereals (Paulitz et al. 2002; Karunarathna et al. 2021).

Table 2. Fungal genera and species on rhizosphere stem and roots on part of the wild grasses

Fungal Genera/ Species	**Rhizosphere Stem* %**			**Roots** %**		
Bipolaris sp.	5,4	±1.1	ab	2,5	±3.5	a
B. sorokiniana	4,5	±1.2	ab	5,3	±0.4	a
Rhizoctonia sp.	5,4	±0.7	ab	5,0	±7.1	a
F. culmorum	0,9	±1.3	a	nd	-	-
F. acuminatum	nd	-	-	2,8	±4.0	a
F. oxysporum	2,2	±0.6	a	nd	-	-
Fusarium sp.	4,5	±1.2	ab	2,5	±3.5	a
GGT***	4,9	±3.2	ab	nd	-	-
Pythium sp.	1,8	±2.5	a	2,8	±4.0	a
A. parasiticus	nd	-	-	2,5	±3.5	a
A. niger	7,9	±3.6	abc	13,6	±12.2	a
Alternaria sp.	0,9	±1.3	a	nd	-	-
Penicillium sp.	12,5	±10.1	c	16,1	±8.6	a
Ganobotrys sp.	5,8	±3.0	ab	2,5	±3.5	a
Phialophora sp.	4,5	±1.2	ab	nd	-	-
Chaetomium sp.	5,8	±4.6	ab	nd	-	-
Conoplea sp.	0,9	±1.3	a	nd	-	-
Torula sp.	4,0	±2.0	ab	15,6	±6.3	a
Periconia sp.	2,2	±0.6	a	nd	-	-
Acremonium sp.	4,5	±1.2	ab	5,0	±7.1	a
Gleocladium sp.	2,7	±3.7	a	nd	-	-
Aurobasidium sp.	2,2	±0.6	a	nd	-	-
Mucor sp.	2,7	±3.7	a	10,6	±0.8	a
Lacellina sp.	1,3	±1.8	a	nd	-	-
Chloridium sp.	1,3	±1.8	a	nd	-	-
Septonema sp.	1,3	±1.8	a	nd	-	-
Sterile	9,7	±1.3	bc	nd	-	-
Bacterial Growth	0,9	±1.3	a	nd	-	-

* There is a significant difference among the variances by statistically, $P<0.05$

** There is no significant differences among the variances by statistically, $P>0.05$

*** *Gaeonomyces graminis* var. *tritici*; nd= not detected

In the wild grasses, the fungal density was founded as the highest range in L. perenne (N=16) with 35.5% and 30.9% both rhizosphere and roots, respectively. This means indicated that L. perenne can provide to favorable host for fungal organisms that living within soil. In the other hand, fungal density in roots of Festuca and Avena was founded higher than that in rhizosphere stem. Bromus, Aegilops and Seceale were in the least hospitality for soil borne fungi (Figure 2).

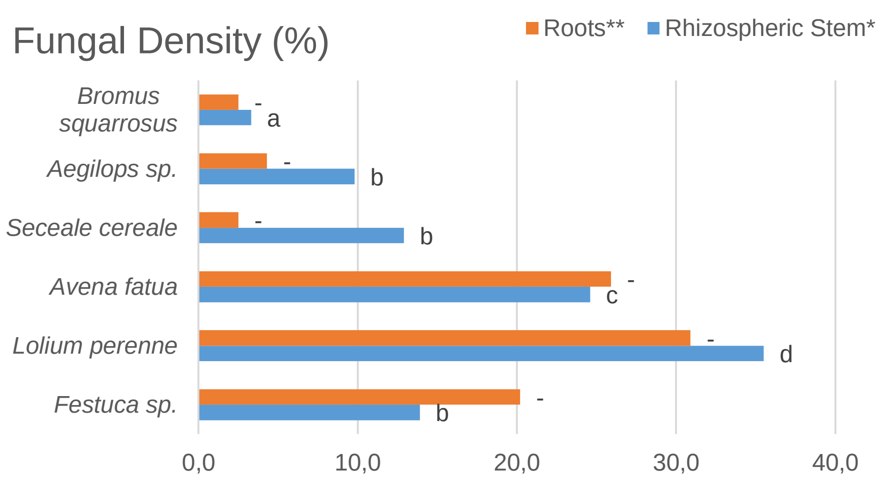


Figure 2. Fungal density (%) obtained from rhizosphere and roots on wild grasses genera/species

Three altitude levels of wild grasses that collected from Türkiye, were defined as A, B and C groups in this study (Table 3.). There is statistically a significant difference among these three altitude levels of the plants according to fungal density. The highest density was founded with 9.9% on grasses that below to one-thousand meters for rhizosphere stems. There are no significant differences for fungal density on any altitude's levels from the roots of wild grasses. Mansour et al. (2012) reported that Fusarium species, a common soilborne pathogen, were the highest density on cultivated and non-cultivated plants at living on 1200 and 1500m altitudes levels. In this study, majority of soilborne pathogen species like Fusarium, Bipolaris, Rhizoctonia, Pythium, and GGT, were obtained at above to 1500m.

Table 3. Fungal density (%) from rhizosphere and roots depends on altitudes levels of wild grasses

Altitude Groups		Rhizospheric Stem* %			Root** %		
0< A ≤1000m	(N=10)	9,9	±5.2	b	10,0	±10.5	a
1100< B ≤1500m	(N=12)	8,4	±3.9	ab	8,3	±5.8	a
C > 1500m	(N=18)	5,6	±3.4	a	5,5	±5.2	a

* There is a significant difference among the variances by statistically, *P*<0.05

** There are no significant differences among the variances by statistically, P>0.05

N= Number of plant samples

Conclusion

The fungal density on wild grasses and their different altitudes levels was investigated in this study. There can be various in the range of fungal density and diversity depending on the altitude levels but is not directly relationship between fungal density and altitudes levels. Also, there is no correlation among the elevation levels for fungal diversity and density. Fungal density was the highest ratio in rhizosphere stem than the roots and soilborne pathogen fungi were mostly colonized in rhizosphere of Festuca and Lolium species.

Out of the Festuca and Lolium species can be able to resist against soilborne pathogens, thus they can have a potential candidate to improvement for the new elite lines and cultivars in plant breeding.

References

Barnett, H. L., Hunter, B. B., 1998. Illustrated Genera of Imperfect Fungi. St. Paul, Minnesota, USA: APS Press., p.218.

Burgess, L. W., Backhouse, D., Summerell, B. A., Swan, L. J., 2001. Crown rot of wheat. In 'Fusarium: Paul E. Nelson memorial symposium' (eds. Summerell B. A., Leslie J. F., Backhouse D., BrydenW.L., Burgess L.W.), APS Press, Minnesota: pp. 271-294.

Cabi, E., Doğan, M., Özler, H., Akaydın, G., Karagöz, A., 2010. Taxonomy, morphology and palynology of Aegilops vavilovii (Zhuk.) Chennav. (Poaceae: Triticeae). African Journal of Agricultural Research, 5(20): 2841-2849.

Crofts, F. C., Esdaile, R. J., Burgess, L.W., 1988. Towards No-Tillage. The University of Sydney, Australia.

Davis, P. H., 1968. Flora of Turkey. Edinburgh, UK: Edinburgh University Press, Vol. 11.

Davis, P. H., 1985. Aegilops L. Flora of Turkey and the East Aegean Islands 9: 233-245, Edinburgh Univ. Press.

Duncan, D. B., 1955. Multiple range and multiple F tests. Biometrics, 11, 1-42.

Gerlach, W., Nirenberg, H. I., 1982. The genus Fusarium — a pictorial atlas (Dahlem ed.). Forstwirtschaft, Berlin – Dahlem: Hrsg. Vond. Biolog. Bundesanst. Für Land-u., p.406.

Karunarathna, A., Tibpromma, S., Jayawardena, R.S., Nanayakkara, C., Asad, S., Xu, J., Hyde, K. D., Karunarathna, S. C., Stephenson, S. L., Lumyong, S., Kumla, J., 2021. Fungal Pathogens in Grasslands. Front. Cell. Infect. Microbiol. 11:695087. doi: 10.3389/fcimb.2021.695087.

Leslie, J. F., Summerell, B. A., 2006. The Fusarium Laborotary Manual. 2121 State Aevue, Iowa, USA: Blackwell Publishing., p.388.

Levene, H., 1960. Robust Tests for Equality of Variances. In I. Olkin (Ed.), Contributions to Probability and Statistics. Palo Alto, California: Stanford University Press. pp. 278-292.

Manshor, N., Rosli, H., Ismail, N. A., Salleh, B., Zakaria, L. 2012. Diversity of Fusarium Species from Highland Areas in Malaysia. Tropical Life Sciences Research, 23 (2): 1-15.

Nano Fertilizers in Plant Nutrition

Füsun GÜLSER *
Van Yüzüncü Yıl University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Van, Türkiye

***Corresponding Author**

Füsun GÜLSER
gulserf@yahoo.com

Abstract
Advances in nanotechnology have improved methods for large-scale production of nanoparticles of physiologically important metals; these are now used in the development of fertilizer formulations to increase uptake into plant cells and minimize nutrient loss. It can produce controlled and delayed release fertilizers using nano particles and nano powders.. Nano materials consist of nano meter-scale particles with a very small diameter and large spesific area. It was reported that nanomaterials have potential applications as crop fertilizers because of their physical and chemical attributes. Nano-fertilizers are syhthesized or modified form of traditional fertilizers, fertilizers bulk materials or extracted from diffeent vegetative or reproductive parts of the plant by diferent chemical, physical, mechanical or biological methods with the helps of nanotechnology used to improve soil fertility. Nano particles can made from fully bulk materials. In recent laboratory-scale studies, it has been reported that nanofertilizers can increase crop productivity by increasing seed germination and seedling rates.

Keywords: Nano materials, fertilizer, plant, nutrition growth

Introduction
Nano fertilizers, defined as fertilizers that utilize nanotechnology to enhance nutrient delivery and uptake in plants, represent a transformative approach in agricultural practices.The global agricultural sector faces significant challenges, including soil degradation, nutrient depletion, and the need for increased food production to meet the demands of a growing population. Traditional fertilizers, while effective in providing essential nutrients, often lead to environmental issues such as nutrient leaching and soil toxicity. In this context, nano fertilizers have emerged as a promising solution, leveraging the principles of nanotechnology to enhance plant nutrition and promote sustainable agricultural practices.

Properties of Nano Fertilizers
Nano fertilizers are characterized by their nanoscale dimensions, typically ranging from 1 to 100 nanometers. This small size confers several advantages, including a high surface area-to-volume ratio, which enhances the reactivity and solubility of nutrients. As a result, nano fertilizers can improve nutrient availability in the soil and facilitate better absorption by plant roots (Sadhukhan et al., 2022; Singh, 2024). Additionally, the controlled release properties of nano fertilizers allow for a gradual supply of nutrients, aligning with the plants' growth stages and reducing the risk of nutrient leaching (Rehana et al., 2022; Hussein & Abou-Baker, 2018).

Mechanisms of Action
The mechanisms through which nano fertilizers enhance plant nutrition are multifaceted. Firstly, the small size of nanoparticles enables them to penetrate plant tissues more effectively, facilitating direct nutrient uptake (Upadhyay et al., 2023). Secondly, nano fertilizers can be engineered to release nutrients in a controlled manner, ensuring that plants receive the necessary nutrients at critical growth stages (Sahana et al., 2023). This targeted delivery system not only improves nutrient use efficiency but also minimizes the environmental impact associated with traditional fertilizer application (Upadhyay, 2023; Sebastian, 2023).

Benefits of Nano Fertilizers
Benefits of nano fertilizers are presented below.

Enhanced Nutrient Use Efficiency

Numerous studies have demonstrated that the application of nano fertilizers can significantly enhance nutrient use efficiency in crops. For example, the use of nano-zinc and nano-urea has been shown to improve biomass and yield in various crops, including cotton and rice, particularly under stress conditions such as salinity and drought (Jithendar, 2024; Vasuki, 2023). The improved nutrient uptake associated with nano fertilizers can lead to higher crop yields and better quality produce (Morsy et al., 2018).

Environmental Sustainability

The environmental benefits of nano fertilizers are noteworthy. By reducing nutrient leaching and minimizing the over-application of fertilizers, nano fertilizers contribute to improved soil health and reduced water contamination (Madlala, 2024). Furthermore, the use of nano fertilizers can decrease the overall quantity of fertilizers needed, thereby lowering the carbon footprint associated with fertilizer production and application (Kumar, 2021).

Improved Soil Fertility

The incorporation of nano fertilizers into agricultural practices has been linked to improvements in soil fertility. By enhancing the availability of essential nutrients, nano fertilizers can promote microbial activity and improve soil structure, leading to long-term benefits for soil health (Kumar et al., 2023; Abdel-Aziz et al., 2016).

Conclusion

Nano fertilizers represent a significant advancement in plant nutrition, offering numerous benefits that align with the goals of sustainable agriculture. Their unique properties facilitate enhanced nutrient uptake, improved crop yields, and reduced environmental impacts. As research continues to explore the full potential of nano fertilizers, their role in modern agriculture is likely to expand, contributing to more efficient and environmentally friendly farming practices.

References

Abdel-Aziz, M. A., et al. (2016). "Nano chitosan-NPK fertilizer enhances the growth and productivity of wheat plants grown in sandy soil." *Spanish Journal of Agricultural Research*. doi:10.5424/sjar/2016141-8205.

Hussein, A. A., & Abou-Baker, M. (2018). "The contribution of nano-zinc to alleviate salinity stress on cotton plants." *Royal Society Open Science*. doi:10.1098/rsos.171809.

Jithendar, K. (2024). "Revolutionizing Crop Nutrition: Exploring Nano Fertilizers in Agriculture." *International Journal of Plant & Soil Science*. doi:10.9734/ijpss/2024/v36i64635.

Kumar, A. (2021). "Nanofertilizers and their role in sustainable agriculture." *Annals of Plant and Soil Research*. doi:10.47815/apsr.2021.10067.

Kumar, A., et al. (2023). "Effect of Organic manure, Bio-fertilizer and Nano-fertilizer on Yield and Economics of different Vegetable crops and soil nutrient status." doi:10.21203/rs.3.rs-2960032/v1.

Madlala, M. (2024). "Examining the Correlation of the Nano-fertilizer Physical Properties and Their Impact on Crop Performance and Nutrient Uptake Efficiency." doi:10.20944/preprints202406.1259.v1.

Morsy, M. K., et al. (2018). "Effect of Irrigation, Foliar Spray with Nano-fertilizer (Lithovit) and N-levels on Productivity and Quality of Durum Wheat under Toshka Conditions." *Assiut Journal of Agricultural Sciences*. doi:10.21608/ajas.2018.14899.

Rehana, S., et al. (2022). "Controlled Release of Nutrients for Soil Productivity

Sadhukhan, A., et al. (2022). "Enhancing the Productivity of Field Crops through Nano-Fertilizer." *Nano-fertilizers and their role in sustainable agriculture*. doi:10.5772/intechopen.101146.

Sahana, S., et al. (2023). "Effect of Nano Nitrogen and Nano Zinc on Soil Fertility and Crop Productivity of Paddy-paddy Cropping System." *International Journal of Plant & Soil Science*. doi:10.9734/ijpss/2023/v35i92910.

Sebastian, A. (2023). "Green synthesis of potassium-infused nitrogenous nano-fertilizer for enhanced plant growth." *Chemical Papers*. doi:10.1007/s11696-023-03175-7.

Singh, R. (2024). "Nanotech for Fertilizers and Nutrients-Improving Nutrient use Efficiency with Nano-Enabled Fertilizers." *Journal of Experimental Agriculture International*. doi:10.9734/jeai/2024/v46i52372.

Upadhyay, S. (2023). "Unveiling the combined effect of nano fertilizers and conventional fertilizers on crop productivity, profitability, and soil well-being." *Frontiers in Sustainable Food Systems*. doi:10.3389/fsufs.2023.1260178.

Upadhyay, S., et al. (2023). "Conjoint application of nano-urea with conventional fertilizers: An energy efficient and environmentally robust approach for sustainable crop production." *Plos One*. doi:10.1371/journal.pone.0284009.

Vasuki, S. (2023). "Influence of Irrigation Methods and Nano-fertilizers Application on the Yield of Transplanted Lowland Rice (Oryza sativa L.) in Periyar Vaigai Command Area of Madurai." *Agricultural Science Digest

Effects of organic and inorganic iron and zinc compounds on active and total iron indices in apple trees

Füsun GÜLSER *
Van Yüzüncü Yıl University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Van, Türkiye

***Corresponding Author**

Füsun GÜLSER
gulserf@yahoo.com

Abstract

This study was carried out in order to determine the effects of organic and inorganic compounds of iron and zinc on quality of Starking apple in a randomized factorial experimental design at the Fruit and Seedling Production Station of Van Provincial Directorate of Agriculture. In the experiment, 290 g N, 260 g P2O5 and 50 g K2O per tree were applied to each plot as a basic fertilization. In soil and foliar fertilization, Bolikel Fe (Fe EDDMa, 6% Fe) and Sanzink (6% Zn) organic compounds were used as chelate forms of iron and zinc, respectively. FeSO4.7H2O (20% Fe) and ZnCl2 (44% Zn) were used as inorganic compounds of iron and zinc, respectively. The effects of different applications on active and total iron contents were found significant at 1 % level statistically. Active iron and total iron index were determined as 7.121 and 1.45, respectively, in the control. The highest and lowest active iron indexes were obtained as 8.26 and 1.12 in sanzink and FeSO4.7H2O applications, respectively. Similarly, the highest and lowest total iron indexes were obtained as 0.42 and 2.12 in sanzink and FeSO4.7H2O applications, respectively.

Keywords: Apple, iron, zinc, fertilization. iron index

Introduction

Iron and zinc are essential micronutrients that play vital roles in various physiological processes in plants, including photosynthesis, respiration, and enzyme function. The forms in which these nutrients are supplied (organic or inorganic) can significantly influence their bioavailability and uptake by plants. Understanding how different iron and zinc compounds affect the active and total iron indices in apple trees is crucial for optimizing nutrient management practices in apple orchards. Organic iron compounds, such as iron chelates, have been shown to enhance the bioavailability of iron in the soil, leading to improved uptake by apple trees. For instance, studies indicate that the application of iron chelates can significantly reduce chlorosis symptoms in iron-deficient apple trees, thereby improving overall tree health and fruit quality (Neilsen et al., 2005). In contrast, inorganic iron sources, such as iron sulfate, may not provide the same level of bioavailability, particularly in high pH soils where iron solubility is reduced (Neilsen et al., 2005). Similarly, organic zinc sources, including zinc chelates and marine algae extracts, have been found to improve zinc nutrition in apple trees more effectively than inorganic zinc sources. Research has demonstrated that foliar applications of organic zinc can enhance leaf zinc concentrations and improve growth parameters in apple trees (KAREEM et al., 2022). This is particularly important as zinc plays a crucial role in enzyme function and photosynthesis, directly impacting fruit yield and quality.

The active and total iron indices in plants are critical for assessing iron nutrition.T he total iron index refers to the overall concentration of iron in plant tissues, while the active iron index indicates the fraction of iron that is readily available for uptake and utilization by the plant. Understanding the effects of iron and zinc compounds on these indices is essential for optimizing nutrient management in agriculture. Research indicates that the application of iron compounds can significantly increase the total iron index in plants. For example, Mazurek (2012) reported that increasing the leaching time of iron compounds resulted in higher concentrations of iron extracted from plant materials. This suggests that the availability of iron can be enhanced through proper management practices. The active iron index is influenced by the form of iron applied These indices help in diagnosing iron deficiency or toxicity in plants. For instance, a low active iron index may indicate that the plant is unable to access sufficient iron, leading to chlorosis and reduced growth Donnini et al. (2003). This highlights the importance of balancing nutrient applications to maintain optimal iron availability. In this study, determination of effects of different iron and zinc compounds on active and total iron index in apple trees was aimed.

Material and Methods

This study was carried out at the Fruit and Sapling Production Station of Van Provincial Directorate of Agriculture. The experiment was conducted according to completely randomized experimental design with four replications in 28 parcels. In this research, 15- 20 years old starking delicious apple trees were used as basic fertilizations 250 g N (as Ammonium Sulphate: 21% N), 250 g, P_2O_5 (as Di Ammonium Phosphate: 18% N, 46% P_2O_5) and 50 g K_2O (as Potassium Sulphate: 50% K_2O) were applied to each trees accepted one parcel. In the experiment, 290 g N, 260 g P_2O_5 and 50 g K_2O per tree were applied to each plot as a basic fertilization. In soil and foliar fertilization, Bolikel Fe (Fe EDDMa, 6% Fe) and Sanzink (6% Zn) organic compounds were used as chelate forms of iron and zinc, respectively. $FeSO_4.7H_2O$ (20% Fe) and $ZnCl_2$ (44% Zn) were used as inorganic compounds of iron and zinc, respectively. Chelated Fe (Botikel, Fe EDDHMa, 6% Fe) and Zn (Sanzink, 6% Zn) fertilizers were applied to soil and leaf as separately, or combine of those for each randomly chosen tree.In the different soil applications 50g Fe chelate and 400 ml Zn chelate were separately solved in 30 L water and were applied to embossed soil surface under tree projection far away from stem in ratio of 1/4 of tree crown projection radius. In the different leaf applications 16 g Fe chelate and 125 ml Zn chelate were separately solved in 10 L water. In different foliar applications, the basis was to dissolve 16 g Bolikel Fe, 50 g $FeSO_4.7H_2O$, 125 ml Sanzink and 100 g $ZnCl_2$ in 10 liters of water per tree, in accordance with the dose recommended in similar studies (Orphanos, 1982; Gediklioğlu, 1990). The compounds were prepared in 5 l of water in the specified proportions and sprayed with a back sprayer until the trees were thoroughly wet. Total doses of leaf applications were applied in two period by 20 days interval before flowering time. Twenty leaves were picked from each tree for chemical analyses. The soil physical and chemical analyses were done by using standard soil analyze methods reported by Kacar (2012). The nutrient analyses were analyzed in dried and grinded leaf samples according to the methods reported by (Kacar and İnal,2008). The active and total iron indices were calculated by using below equation reported by Urresterazu et al (1994).

$$Fe\ I = (10\ P\ (\%\ d.v.) + K\ (\%\ d.v.)) \cdot 50 / Fe\ mg\ kg^{-1}$$

Statistical analyses of obtained data were done by using SAS package program (SAS, 1998). Application means were compared with Duncan's test.

Results and Discussion

Physical and chemical soil properties of garden soil had sandy loam, sandy clay loam in texture, slightly alkaline, slightly saline, moderate limely, insufficient in potassium and zinc contents.

The statistical analyses results of obtained data were given in Table 1.

Table 1. Variance analysis table for the effect of applications on active total iron index

Source	DF	Active Iron Index		Total Iron Index	
		MS	F	MS	F
Treatments	6	165.871	74.51**	8.402	32.90**

**: significant at 1% level

The effects of different applications on active and total iron contents were found significant at 1 % level statistically.

The phosphorus , potassium, active and total iron contents used in index calculations were given in Figure 1, 2, 3, 4.

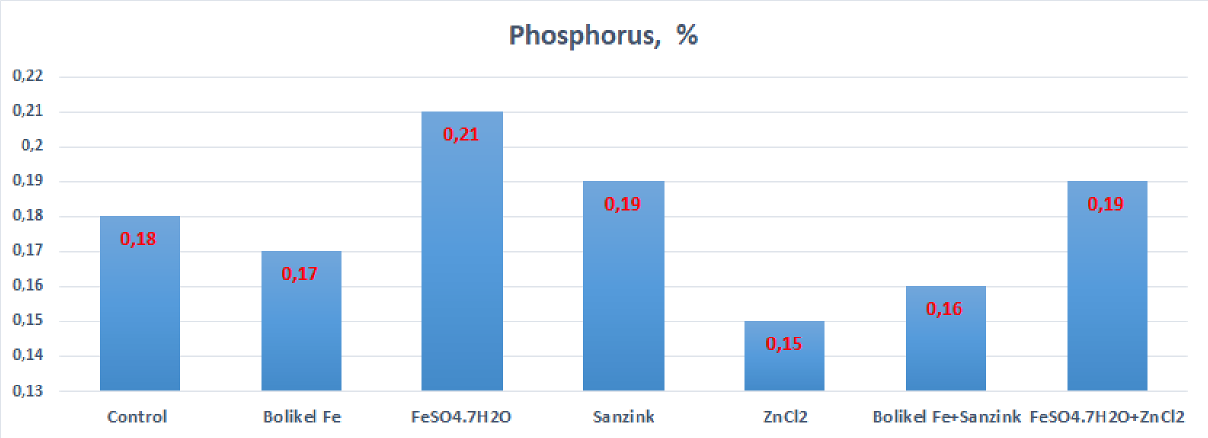


Figure 1. Effects of organic and inorganic iron and zinc applications on leaf phosphorus contents.

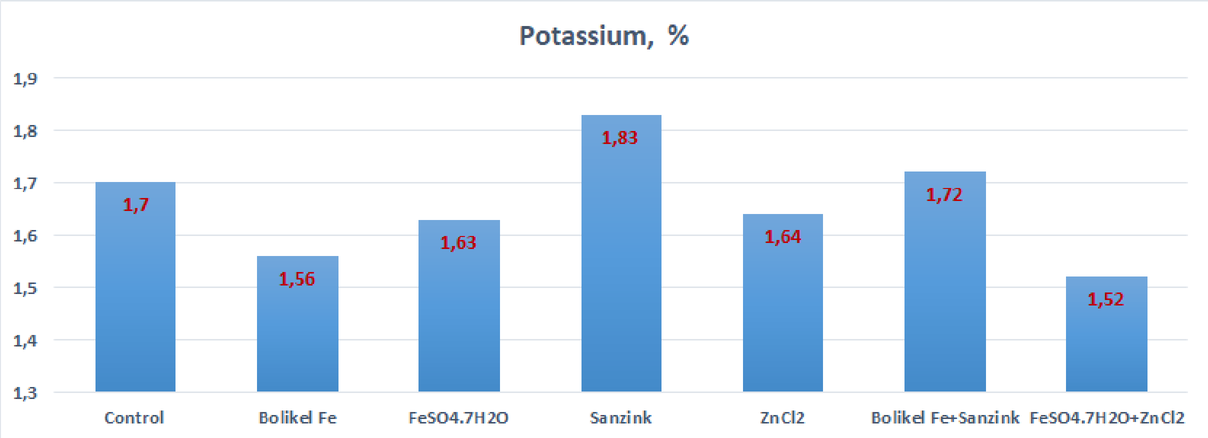


Figure 2. Effects of organic and inorganic iron and zinc applications on leaf potassium contents.

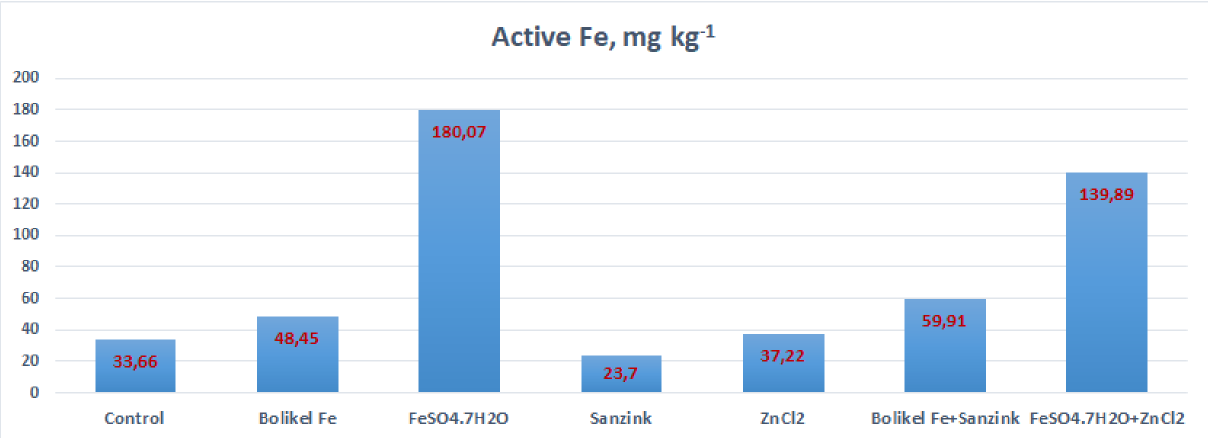


Figure 3. Effects of organic and inorganic iron and zinc applications on leaf active iron contents

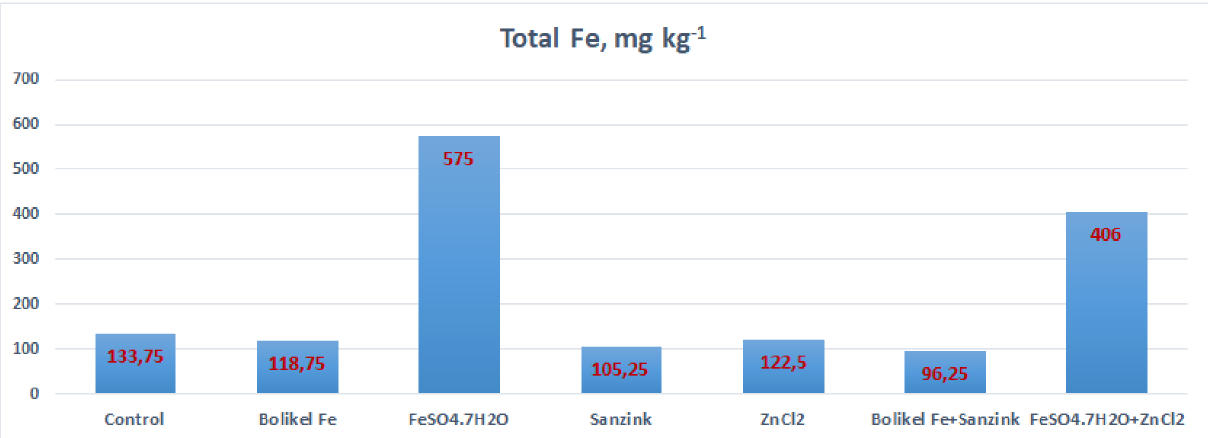


Figure 4. Effects of organic and inorganic iron and zinc applications on leaf total iron contents.

The active and total iron contents obtained in different applications were given in Figure 5,6.

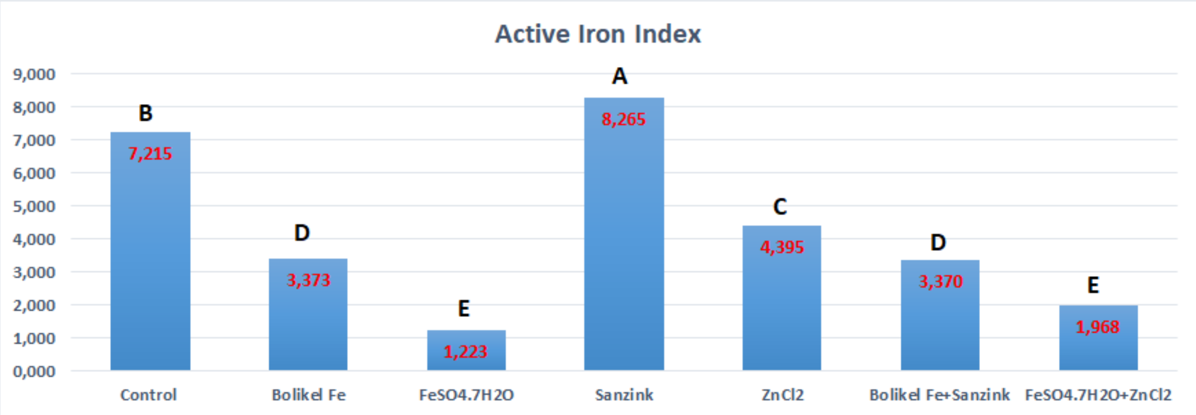


Figure 5. Effects of organic and inorganic iron and zinc applications on active iron iron indices.

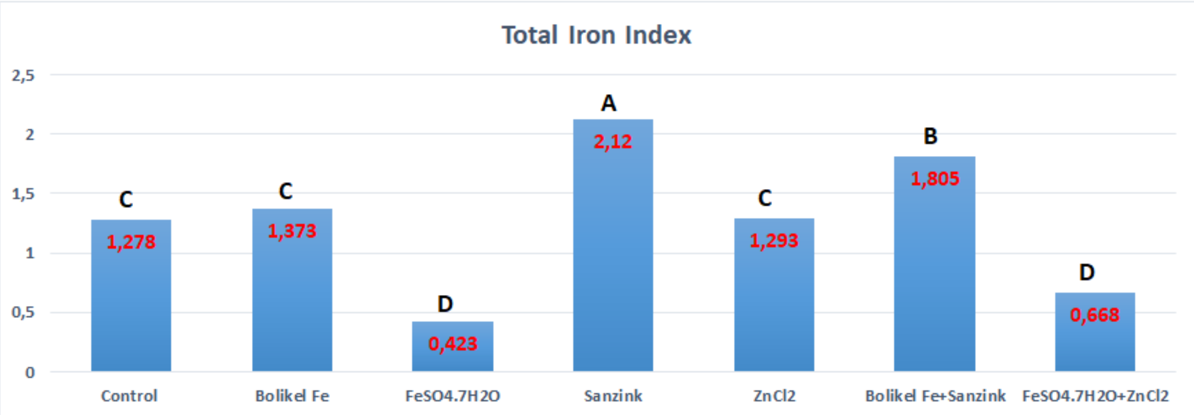


Figure 6. Effects of organic and inorganic iron and zinc applications on total iron indices.

When the obtained data were evaluated according to optimum values (0.93- 1.02) reported by Urresterazu et al (1994) active and total iron indices in FeSO4.7H2O applications were found within threshold values (<1.03). The zinc compounds applicated alone or combine iron compounds leaded increases in active and total iron indices. It was thought that this situation may be caused from antagonistic relations between iron and zinc. The relationship between iron and zinc is characterized by competition for absorption. Sahana et al., (2023) reported that excessive zinc can inhibit iron uptake, leading to deficiencies in iron, particularly in plants grown in zinc-rich soils. Felix et al. (2020) observed that higher doses of iron could lead to decreased levels of other minerals, such as zinc, indicating an antagonistic relationship that can affect the active iron index (Singh, 2024).

Conclusion

Active and total iron indices are essential metrics for assessing iron nutrition in plants. Understanding these indices allows for better management of iron availability, leading to improved plant health and agricultural productivity. Understanding the dynamics of iron uptake and utilization can guide the development of new fertilizers and soil amendments that enhance iron bioavailability, ultimately improving agricultural productivity (Varotto et al., 2002). Monitoring these indices can inform soil management practices. For example, if total iron levels are high but active iron levels are low, it may indicate that the iron is in an unavailable form, prompting the need for soil amendments or chelation strategies (Metwally, 2023). Future research should focus on developing strategies to enhance iron bioavailability in various soil types and under different environmental conditions.

References

Donnini, S., et al. "Leaf Responses to Reduced Iron Availability in Two Tomato Genotypes: T3238*FER* (Iron Efficient) and T3238*fer* (Iron Inefficient)," *Journal of Plant Nutrition*, vol. 26, no. 4, pp. 657-670, 2003. doi:10.1081/pln-120024270.

Felix, M., et al. "Edaphic and Foliar Biofortification of Common Black Bean (Phaseolus vulgaris L.) with Iron," *Legume Research*, 2020. doi:10.18805/lr-553.

Gedikoğlu İ,1990. Ankara yöresinde armut ağaçlarında görülen mikro besin maddeleri noksanlıklarının teşhisi ve tedavisi. Toprak ve Gübre Araştırma Enstitüsü Yayınları. Genel Yayın No: 163. Rapor Seri No: 85.

Kacar B., İnal A. 2008. Plant Analysis. Nobel Publication No: 1271, Science: 63, 2008

Kacar, B., 2012. Toprak Analizleri. Nobel Akademik Yayıncılık, Yayın No: 484, Ankara.

Kareem, K. A., Alojany, Z. O. O., & Al-Janabi, A. S. A. (2022). Marine algae extracts, and nano fertilizer with zinc and copper effects on growth, and macro-and micronutrients composition of apple trees.

Mazurek, "Extraction of vanadium and potassium compounds from the spent vanadium catalyst from the metallurgical plant," *Polish Journal of Chemical Technology*, vol. 14, no. 1, pp. 1-6, 2012. doi:10.2478/v10026-012-0070-9.

Metwally, A. 2023. Effect of Iron Concentration in the Nutrient Solution and Irrigation Scheduling on Strawberry Plants Grown in Hydroponics, Zagazig Journal of Agricultural Research*, vol. 50, no. 1, 2023. doi:10.21608/zjar.2023.323797.

Neilsen G.H., Hogue E.J., Neilsen D., Bowen P., 2005. Postbloom humic- and fulvic-based zinc sprays can improve apple zinc nutrition. HortScience 40, 205-208.

Orphanos PL,1982. Spray and soil application of zinc to apples. Journal of Horticultural Science. 57(3): 259-266.

Singh, A. K. (2024). Impacts of Minerals on the Plant's Growth and Metabolism. Addition Publishing House.

Urrestarazu, M., Sanchez, A., Alvarado, J., & Romero, L. (1994). Iron indices and micronutrients in deciduous fruit trees. Communications in Soil Science and Plant Analysis, 25(9-10), 1685-1701.

Varotto, C., et al. "The Metal Ion Transporter IRT1 is Necessary for Iron Homeostasis and Efficient Photosynthesis in *Arabidopsis thaliana*," *The Plant Journal*, vol. 30, no. 2, pp. 217-229, 2002. doi:10.1046/j.1365-313x.2002.01381.x.

International Soil Science Symposium on
"SOIL SCIENCE & PLANT NUTRITION"
(10th International Scientific Meeting)

13-14 December 2024 / Samsun, Türkiye