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EURASIAN SOIL CONGRESS 2025

International Congress on
"Innovations in Soil Science and Plant Nutrition under Climate Change"

1 – 4 September 2025
Ondokuz Mayıs University, Samsun, TÜRKİYE

11th

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"Innovations in Soil Science and Plant Nutrition under Climate Change"
EURASIAN SOIL Congress 2025

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11th International Congress
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Preface I

Distinguished Participants,

It is with great pleasure and honor that I welcome you to the 11th International Congress on Innovations in Soil Science and Plant Nutrition under Climate Change (Eurasian Soil Congress 2025), held on 1–4 September 2025 in Samsun, Türkiye, under the auspices of Ondokuz Mayıs University, in collaboration with the Soil Science Society of Turkey (SSST), the Federation of Eurasian Soil Science Societies (FESSS), and the Erasmus Mundus Master in Soil Science (emiSS) program.

This congress serves as a significant platform for scientists, researchers, policymakers, and industry representatives to exchange knowledge, share experiences, and discuss the latest advances in soil science, plant nutrition, and sustainable agricultural practices under the challenges of climate change. The participation of delegates from various countries reflects the truly international nature of our scientific community and fosters cooperation beyond borders.

Following the evaluation process by the Scientific Committee, a total of 87 papers submitted by researchers from 18 different countries have been accepted for presentation—either as oral or poster sessions—at this congress. This number clearly demonstrates both the scientific diversity and the global relevance of our meeting.

The Abstract Book compiles the summaries of all accepted oral and poster presentations, offering an overview of the diversity and depth of topics addressed during the congress. The Book of Proceedings further extends this knowledge base by publishing full-text contributions, ensuring that the valuable findings presented here remain accessible to the scientific community for years to come.

On behalf of the Organizing Committee, I express my deepest gratitude to all authors, reviewers, session chairs, invited speakers, and sponsors whose efforts have contributed to the success of this congress. I also extend my sincere appreciation to our international and national participants for their interest, enthusiasm, and active engagement.

It is my hope that the ideas and collaborations generated during this congress will inspire new research, innovative practices, and sustainable solutions to the pressing challenges facing our soils and agricultural systems in a changing climate.

I wish you all an intellectually stimulating and fruitful congress, and I look forward to the outcomes and collaborations that will emerge from our discussions in Samsun.

Prof. Dr. Rıdvan Kızılkaya
Chair of the Congress
Eurasian Soil Congress 2025

Preface II

Dear participants,

It is my great pleasure to attend the International Congress on “Innovations in Soil Science and Plant Nutrition under Climate Change” as a part of organizing committee. This Congress has been organized by the Federation of Eurasian Soil Science Societies (FESSS) collaborating with ERASMUS MUNDUS Joint Master Degree in Soil Science (emiSS) programme. The emiSS programme has been founded with the support of the Erasmus+ Programme of the European Union and organized by a consortium of the universities: Ondokuz Mayıs University (OMU-Turkey), University of Agriculture in Krakow (UAK-Poland), Agricultural University Plovdiv (AU - Bulgaria), Southern Federal University (SFedU - Russia) and Jordan University of Science and Technology (JUST- Jordan) in 2019. The aim of emiSS programme is to raise and meet the need for qualified and skilled soil scientists at the master level through a higher educational programme under the training in soil science, soil management, soil fertility, soil ecosystem with intercultural competence and language skills. So far, 73 international students from the different geographical parts of the World (Europe, Africa, Latin America, Central Asia, Pacific’s, Middle East etc.) have been graduated with MSc degree in Soil Science between 2020-2025. Some of emiSS students are among us and make an oral presentation during the Congress. I hope that the mission of the congress will be successful with sharing novel access that fulfill the needs of applications in soil science and plant nutrition field, and identifying new directions for future researches and developments in soil science area. At the same time, this symposium will give researchers and participants a unique opportunity to share their perspectives with others interested in the various aspects of soil science. I hope this symposium also will be helpful to increase young soil scientists’ knowledge and their presentation skills front of the audience. Once more I would like to thank the all supporting organizations and all participants to their helps and sharing their scientific knowledge in this congress.

Prof.Dr.Coşkun GÜLSER
emiSS Coordinator

Preface III

Distinguished Scientists and Dear Participants,

On behalf of the Eurasian Soil Science Federation, it is my great honor to welcome you all to the 11th International Eurasian Soil Congress and this significant scientific gathering with the theme "Innovations in Soil Science and Plant Nutrition under Climate Change", here in Samsun, on the beautiful shores of the Black Sea.

This congress is not merely a scientific meeting, but also a global platform that brings together collective wisdom, science, and innovative solutions for our common future. Soil is the foundation of agriculture, ecosystems, and human life. Yet today, global challenges such as climate change, increasing population pressure, soil degradation, water scarcity, and biodiversity loss seriously threaten the productivity and sustainability of soils. Therefore, the discussions we will have here and the solutions we will generate are of vital importance, not only from an academic standpoint but also in socio-economic and environmental contexts. The theme of our congress aims to address innovative approaches in soil science and plant nutrition, particularly in the context of adaptation to and mitigation of climate change. Today, a wide range of scientific presentations will be delivered, covering topics from precision agriculture technologies to the use of biofertilizers and biostimulants, and from the development of carbon sinks to circular economy models. These approaches will enable us to take important steps toward both increasing production efficiency and protecting soil health.

Interdisciplinary cooperation is crucial in mitigating the impacts of climate change and ensuring the sustainability of agricultural production. We must integrate knowledge from geology, ecology, microbiology, chemistry, engineering, and the social sciences into a holistic perspective of soil science. This congress provides a valuable opportunity to bring together scientists, researchers, policymakers, and private sector representatives from different disciplines, allowing us to develop comprehensive and applicable solutions for the future.

The Eurasian region is uniquely rich in terms of agricultural production, biodiversity, and natural resources. However, this richness also comes with shared challenges. Threats such as soil erosion, salinization, organic matter loss, acidification, and pollution know no borders. Therefore, our solutions must be shaped through international solidarity and knowledge sharing. In this regard, this congress stands as one of the best examples of scientific diplomacy.

The historical and cultural heritage of Samsun adds a special value to our congress. This beautiful city of the Black Sea is a developed center in many areas, from agricultural production to industry, and from natural resources to cultural heritage. I believe that the scientific discussions to be held here will pave the way for new collaborations on both regional and global scales. Before I conclude, I would like to thank the entire organizing committee, scientific boards, our sponsors, and all researchers who have contributed to the organization of this congress. I wish that our scientific exchanges will be fruitful and lead to new friendships and collaborations.

I wish you all a successful, productive, and inspiring congress. Thank you.

Prof. Dr. Ayten NAMLI,
President of the Soil Science Society of Türkiye (SSST)
President of the Federation of Eurasian Soil Science Societies (FESSS)


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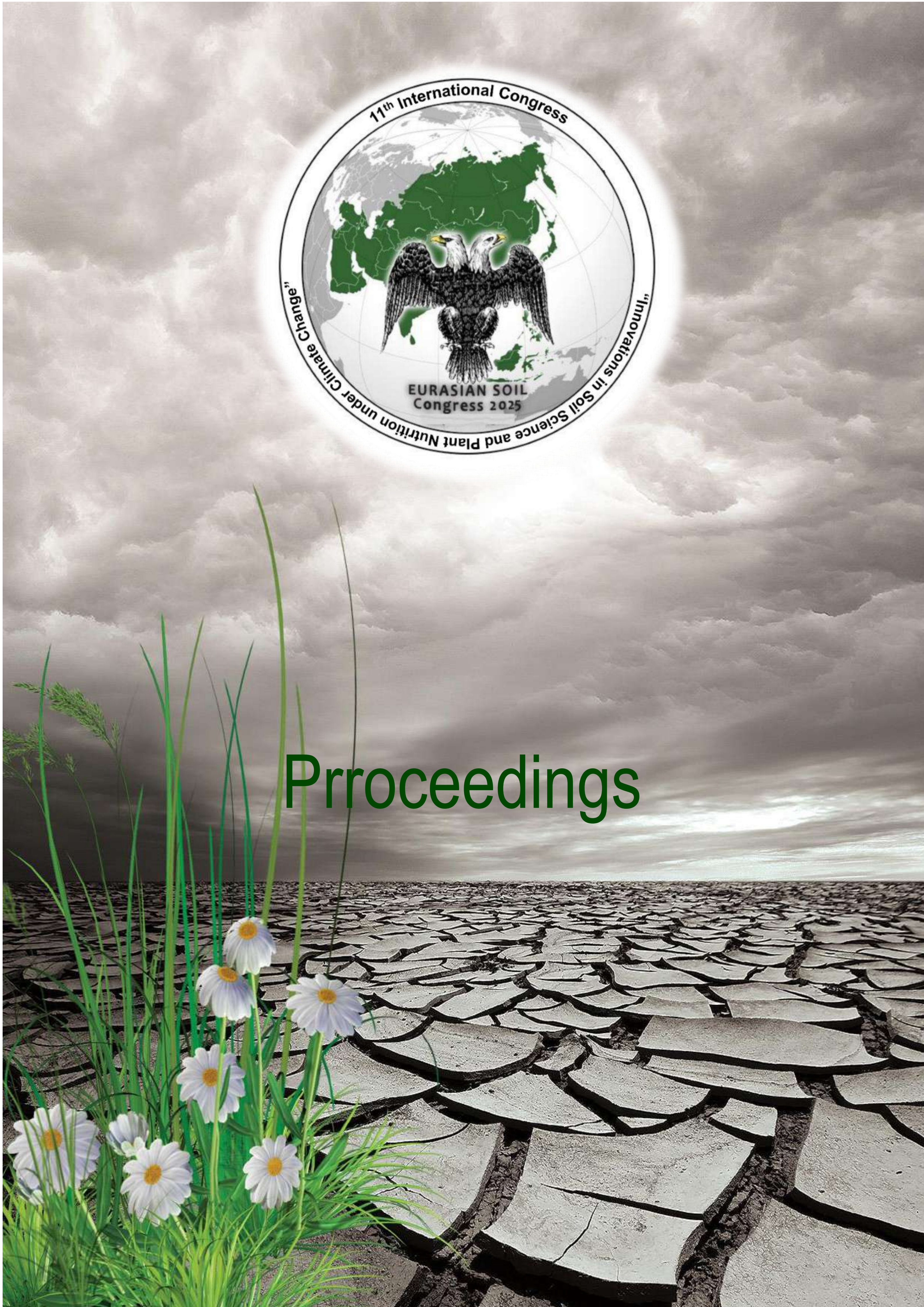

Prroceedings

The effect of clinoptilolite on the movement of nickel heavy metal in soil and plants

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Abstract

Soil contamination, particularly the accumulation of heavy metals, poses a significant threat to environmental sustainability and agricultural productivity. Nickel (Ni), a heavy metal, is naturally present in soils; however, its concentration can increase due to industrial pollution, excessive fertilizer use, and mining activities, leading to toxic effects on plants. Heavy metal toxicity negatively impacts plant growth and development by reducing nutrient uptake, decreasing biomass production, and adversely affecting germination rates. Furthermore, it disrupts various metabolic activities in plants, thereby reducing overall productivity. Zeolite minerals, particularly clinoptilolite, offer an effective solution by enhancing the adsorption of heavy metals in the soil. This study aims to determine the critical threshold of nickel toxicity in wheat plants and evaluate the potential of clinoptilolite in mitigating Ni toxicity. The experiment was conducted in two stages. In the first stage, Ni toxicity in plants was assessed by applying 0-5-10-15-20-25-30-40-50-60-70-100-150-200-300 500-750-1000 mg/kg Ni of $NiSO_4 \cdot 6H_2O$ solution to the soil. Germination rates, biomass production, and Ni concentrations in plant tissues were measured. Results revealed that the lowest germination rate was observed in soil containing 200 mg/kg Ni, demonstrating the toxic effect of Ni. In the second stage, clinoptilolite (Ø<200 µm) was applied to soils containing 200 mg/kg Ni at doses of 25-50-100-150 ve 200 kg/da. Among the clinoptilolite treatments, the lowest plant tissue Ni content was recorded at 50 kg/da (36.969 mg/kg). The findings suggest that clinoptilolite reduces the uptake of Ni by plants but exhibits complex, dose-dependent effects on biomass production. The application of 50 kg/da clinoptilolite resulted in low Ni uptake and high biomass yield, indicating its potential as an optimal balance point for plants. However, the potential effects of clinoptilolite on the availability of essential micronutrients should be considered and validated through further comprehensive studies.

Keywords: Clinoptilolite, heavy metal, nickel toxicity, nickel uptake, pot experiment, soil, wheat.

Introduction

Soil pollution currently poses a serious threat both in terms of environmental sustainability and agricultural production. Among the various causes of soil pollution, heavy metal contamination stands out as a significant factor. The accumulation of heavy metals in the soil adversely affects the quality and yield of crop production, and can also have indirect impacts on human health through the food chain. One such heavy metal, nickel (Ni), becomes toxic to plant growth when present in the soil above a certain threshold. It reduces germination rates,

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decreases biomass production, and negatively influences nutrient uptake. These toxic effects of nickel are particularly pronounced in soils with low pH and low organic matter content.

Ensuring the sustainability of agricultural production requires not only a focus on crop yield but also on food safety and soil health. In this context, physical, chemical, and biological methods are being developed to combat heavy metal contamination, with cost-effective and environmentally friendly solutions gaining increasing importance. One such approach involves the application of materials to reduce the mobility of heavy metals in the soil solution and to limit their uptake by plants.

Due to their natural origin, environmental compatibility, and economic feasibility, zeolite minerals have emerged as promising candidates in this area. Zeolites are effective in adsorbing heavy metals owing to their high surface area, ion exchange capacity, and porous structure. Among these, clinoptilolite is considered a highly potential material for agricultural use because of its abundant natural availability and compatibility with soil. Turkey, especially in its Western Anatolia and Thrace regions, hosts extensive clinoptilolite reserves, providing a strong foundation for research in this field.

This study aims to evaluate the potential of clinoptilolite to mitigate the toxic effects of nickel in the soil on wheat plants, through pot experiments. The experiments were designed in two stages: the first stage aimed to determine the toxicity threshold of nickel, while the second stage investigated the effects of clinoptilolite applications on this toxicity. The findings are significant in revealing the role of clinoptilolite in terms of both plant development and soil health.

Material and Methods

The study was conducted in two successive stages to evaluate the effect of clinoptilolite on Ni toxicity in wheat.

Stage I – Determination of Ni Toxicity Threshold

The first stage aimed to identify the soil Ni concentration that induces toxicity symptoms in wheat. The experiment was carried out in the Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Ege University. A soil with low natural Ni content (Total Ni: 4.36 mg/kg; sand: 60.45%, silt: 21.18%, clay: 18.37%; pH: 5.12) was used as the growth medium.

Standard plastic pots were filled with 500 g of soil (Figure 1). Nickel was applied to the soil in the form of $NiSO_4 \cdot 6H_2O$ at the following concentrations: 0, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 100, 150, 200, 300, 500, 750, and 1000 mg Ni/kg soil. The experiment was arranged in a completely randomized design with 18 treatments and 3 replicates, resulting in a total of 54 pots.

Figure 1. The production pot used in the experiment.

Wheat (Triticum aestivum L.) was used as the test plant. Twenty seeds were sown in each pot on July 30, 2024. After 30 days, germinated seedlings were harvested, and germination rate, fresh biomass, and dry biomass were recorded (Figure 2).

Figure 2. General view of the experiment.

Stage II – Evaluation of Clinoptilolite Application

Based on the results from Stage I, 200 mg Ni/kg soil was selected as the toxic concentration for the second experiment. The same soil type and experimental conditions were used. In addition to the control, clinoptilolite (originating from Gördes, particle size Ø<200 µm) was applied at five different doses: 25, 50, 100, 150, and 200 kg/da (Figure 3).

Figure 3. The zeolite clinoptilolite mineral used in the experiment.

Each pot was again filled with 500 g of soil and sown with 20 wheat seeds. The experimental design included 6 treatments (including control) and 3 replicates, for a total of 18 pots.

On the 30th day, plants were harvested by cutting at the soil surface. Germination percentages, fresh and dry biomass values were measured.

For Ni determination in plant tissues, wet digestion was performed using a HNO_3:$HClO_4$ (4:1) mixture, following the method described by Kacar and Inal (2008). Nickel concentrations in the digests were analyzed using Atomic Absorption Spectrophotometry.

All data were analyzed using ANOVA under a completely randomized design, and treatment means were compared using the Least Significant Difference (LSD) test at a 5% significance level.

Results and Discussion

Table 1. Effects of Ni concentrations on germination and fresh biomass of wheat plant.

Soil Ni Concentration (mg/kg)	Germination Count	Fresh Biomass (g/pot) /20 Seeds
0 (Kontrol)	13,00±4,58	0,178±0,111
5	17,00±1,73	0,303±0,056
10	12,33±2,52	0,262±0,108
15	17,33±1,53	0,295±0,063
20	17,33±2,89	0,230±0,027
25	17,33±2,52	0,326±0,072
30	13,00±2,65	0,214±0,036
40	16,00±3,61	0,239±0,029
50	14,33±1,15	0,243±0,067
60	13,00±2,00	0,312±0,069
70	10,33±1,15	0,255±0,041
100	12,33±0,58	0,284±0,041
150	11,00±2,65	0,252±0,099
200	9,00±3,61	0,224±0,058
300	16,33±0,58	0,362±0,053
500	13,33±2,52	0,480±0,182
750	14,67±3,51	0,623±0,366
1000	12,67±3,79	0,363±0,111

As seen in Table 1 and Figure 1, the lowest germination occurred in the soil containing 200 mg/kg of Ni. The average germination count in this treatment was 9, which was the lowest among all applications. Although an increase in Ni concentration in the soil initially led to a rise in germination numbers compared to the control, a decreasing trend was observed at higher Ni levels. The results indicate that the treatment with 200 mg/kg Ni showed the lowest germination rate, revealing that this dose constitutes a distinct toxicity threshold for wheat. The reduction in germination rate and fresh biomass suggests that nickel adversely affects plant metabolism and root-shoot development. In the second stage of the study, this dose was taken into consideration for further application.

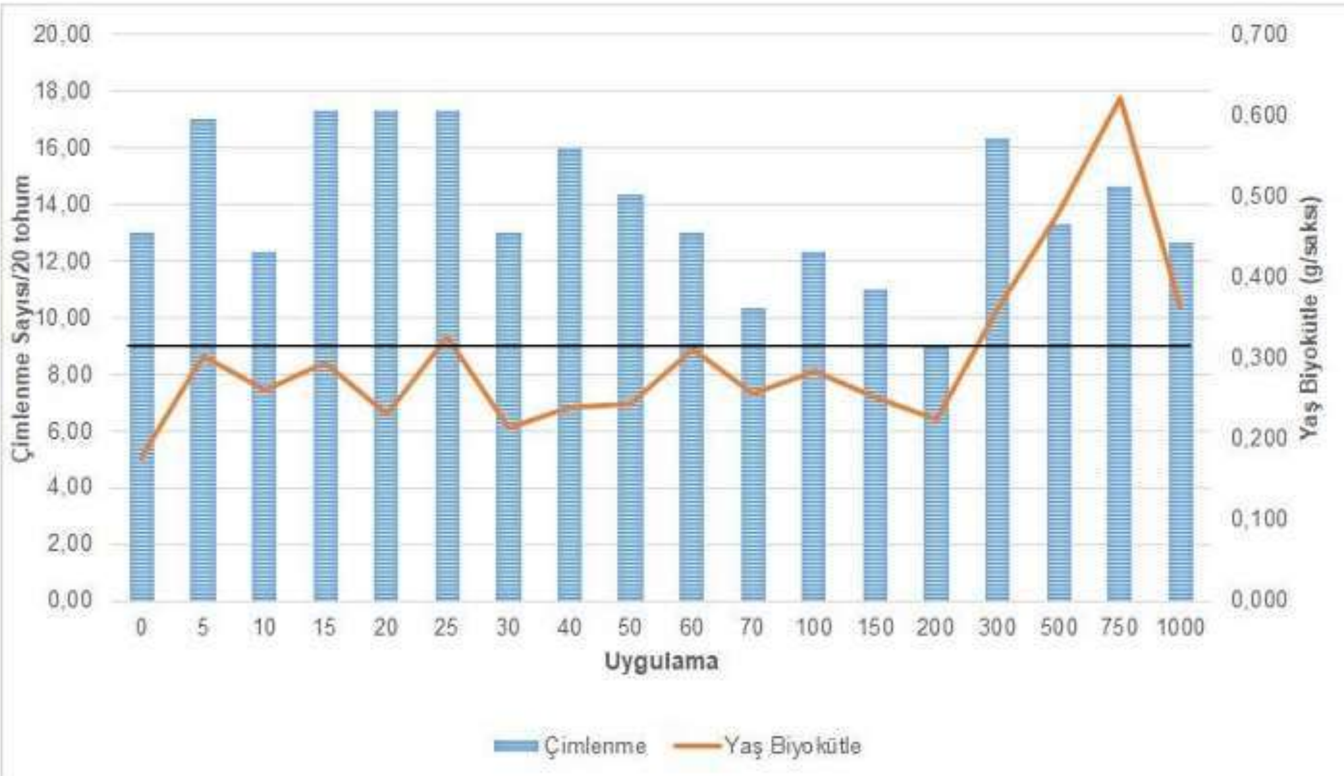

Figure 4. Effects of increasing Ni levels in soil on germination and fresh biomass of wheat plant.

In the second stage of the study, a solution was prepared from $NiSO_4 \cdot 6H_2O$ to achieve a soil Ni concentration of 200 mg/kg, and this solution was applied in liquid form. Under laboratory conditions, increasing doses of clinoptilolite were mixed into the Ni-treated soils. Subsequently, the pots were subjected to two cycles of wetting and drying. Then, 20 seeds were sown in each pot, and the experiment was initiated. The highest germination rate was observed in the treatment without any clinoptilolite application (Table 2). Germination in the control treatment was determined as an average of 14.667 out of 20 seeds. The next highest germination was observed in the treatment with 50 kg/ha clinoptilolite application. This suggests that clinoptilolite at this dose is effective in limiting nickel uptake by the plant. On the other hand, the low germination rate and high nickel content in plant tissue observed at the 25 kg/ha dose indicate that this amount provides insufficient binding capacity and fails to prevent toxicity.

Table 2. Effects of zeolite applications on germination of wheat plant.

Clinoptilolite (kg/da)	Germination Count/20seeds	
0 (Control)	14,667	a
25	4,333	b
50	11,333	ab
100	10,000	ab
150	10,333	ab
200	7,500	ab
	$LSD_{0,01}$: 7,458	

The lowest Ni concentration in plant tissue was determined in the treatment with 50 kg/ha clinoptilolite application (Table 3). In this treatment, the Ni content in the plant tissue was measured as 36.969 mg/kg. It has been reported that Ni levels in cereal leaves grown in areas polluted by the metal industry can reach 230-250 mg/kg (Kabata-Pendias, 2011). Although the findings from this study do not reach these values, the Ni concentration in plant tissue under the 25 kg/ha clinoptilolite treatment reached 130 mg/kg.

Table 3. Effects of zeolite applications on nickel concentration in wheat plant.

Clinoptilolite (kg/da)	Ni (mg/kg)	
0 (Control)	54,404	b
25	130,016	a
50	36,969	b
100	76,424	ab
150	61,247	b
200	59,643	b
	$LSD_{0,05}$: 67,787	

Statistically significant differences were observed between clinoptilolite applications and fresh biomass values in the study. The highest fresh biomass value was recorded in the control treatment, with 2.333 g/pot (Table 4). The lowest fresh biomass was observed in the 25 kg/ha clinoptilolite application, measuring 0.593 g/pot.

Table 4. Effects of zeolite applications on fresh biomass of wheat plant.

Clinoptilolite (kg/da)	Fresh Biomass (g/pot)	
0 (Control)	2,333	a
25	0,593	b
50	1,603	ab
100	1,640	ab
150	1,600	ab
200	0,810	b
	$LSD_{0,01}$: 1,250	

Within the scope of the project, the highest dry biomass value was observed in the control treatment (Table 5). The highest dry biomass, determined as 0.277 g/pot in the control, was followed by the 50 kg/ha clinoptilolite treatment with 0.203 g/pot. The lowest dry biomass value was recorded in the 25 kg/ha clinoptilolite treatment.

Table 5. Effects of zeolite applications on dry biomass of wheat plant.

Clinoptilolite (kg/da)	Dry biomass (g/pot)	
0 (Control)	0,277	a
25	0,070	b
50	0,203	ab
100	0,180	ab
150	0,200	ab
200	0,105	b
	$LSD_{0,01}$: 0,155	

The fact that the control treatment had the highest values in both fresh and dry biomass suggests that clinoptilolite application may have limited plant growth at certain doses. This raises the possibility that clinoptilolite could reduce the availability of micronutrients such as Fe, Zn, Cu, and Mn. It is known that the ion exchange capacity of zeolite minerals is not limited to heavy metals but can also interact with beneficial elements. Therefore, the potential of clinoptilolite to both bind toxic elements and alter the dynamics of plant nutrient availability should be evaluated together.

The observation that the total amount of nickel removed from the soil was highest in the control group, and that this value generally decreased with clinoptilolite applications, suggests that clinoptilolite reduces nickel uptake by plants (Table 6). However, this trend did not show a clear linear decrease across all doses.

Table 6. Effects of zeolite applications on the amount of Ni uptake by wheat plant.

Klinoptilolit (kg/da)	Ni (g/saksı)	
0 (Kontrol)	0,014	a
25	0,005	b
50	0,007	ab
100	0,013	a
150	0,012	a
200	0,005	b
	$LSD_{0,01}$: 0,007	

Conclusion

The findings indicate that clinoptilolite can be an effective measure against nickel toxicity when used at appropriate doses; however, it should be noted that this effect is dose-dependent and may have negative impacts on plant growth at certain doses. Furthermore, the effects of these applications on nutrient balance should be examined in detail through further studies.

Acknowledgment

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Optimizing Foliar Micronutrient Application to Improve Sugar Beet Yield and Quality in Southeastern Kazakhstan

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Abstract

This study investigates the impact of boron and zinc foliar fertilizers on the productivity of sugar beet hybrids Bolashak and Abulkhair in southeastern Kazakhstan. Foliar applications of YaraVita Bortrac150 (B) and Zintrac700 (Zn) were tested individually and in combination on two domestic hybrids using a randomized complete block design. Results indicated that combined micronutrient treatments significantly improved root yield (up to 82.0 t ha^{-1}), sugar content (up to 18.1%), and sugar yield (up to 14.8 t ha^{-1}), especially under NPK background fertilization. The study demonstrates that foliar application of B and Zn is an effective agronomic approach to enhance sugar beet productivity under semi-arid conditions.

Keywords: Sugar beet, boron, zinc, foliar application, yield, sugar content.

Introduction

Sugar beet (Beta vulgaris L.) is one of the most economically significant crops in Kazakhstan's agriculture, contributing substantially to the national sugar production. Despite its importance, the crop's productivity is highly dependent on effective fertilization strategies. In particular, micronutrient deficiencies especially of boron (B) and zinc (Zn) are common in the soils of southeastern Kazakhstan, limiting sugar beet yield and quality. Boron is essential for sugar translocation and reproductive development, while zinc is crucial for enzyme activation, chlorophyll production, and stress resistance. Addressing these deficiencies through foliar application can be a cost-effective and efficient solution. This study investigates the effectiveness of different doses and combinations of boron and zinc foliar fertilizers on sugar beet yield and sugar accumulation under semi-arid conditions.

Material and Methods

Site Description and Experimental Design

Soil samples were collected before sowing to determine nutrient status. Plant tissues (roots and tops) were sampled at different stages to assess B and Zn concentrations using atomic absorption spectrophotometry. Root yield was measured at technical maturity by weighing harvested roots from designated plots. Sugar content was determined via polarimetry following ICUMSA standards. Sugar yield was calculated as root yield × sugar content. Statistical analysis was conducted using SPSS with significance tested at $p < 0.05$.

Data Collection And Analysis

Soil samples were collected before sowing to determine nutrient status. Plant tissues (roots and tops) were sampled at different stages to assess B and Zn concentrations using atomic absorption spectrophotometry. Root yield was measured at technical maturity by weighing harvested roots from designated plots. Sugar

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content was determined via polarimetry following ICUMSA standards. Sugar yield was calculated as root yield × sugar content. Statistical analysis was conducted using SPSS with significance tested at $p < 0.05$.

Results and Discussion

Micronutrient Uptake and Accumulation

Improvement Foliar micronutrient application had a clear positive impact on yield and quality. Bolashak exhibited the highest root yield (82.0 t ha^{-1}), sugar content (18.1%), and sugar yield (14.8 t ha^{-1}) under combined B+Zn application. Abulkhair also showed strong performance with 80.9 t ha^{-1} root yield and 14.4 t ha^{-1} sugar yield under the same treatment. The observed increase in sugar content of 0.5–0.9% over the control is consistent with the role of B and Zn in sucrose metabolism. Additionally, treated plants had reduced contents of nonesugar impurities such as potassium, sodium, and alpha-amino nitrogen, improving technological sugar quality. This supports the hypothesis that balanced micronutrient application enhances both quantitative and qualitative parameters in sugar beet.

Yield and Sugar Quality

Bolashak outperformed Abulkhair in nearly all measured parameters, highlighting the importance of genotype-specific nutrition strategies. Although both hybrids responded positively to micronutrient treatments, Bolashak's higher uptake and accumulation of B and Zn resulted in better yield and sugar output. The findings suggest that micronutrient fertilization should be optimized based on hybrid-specific requirements. In Kazakhstan's semi-arid agricultural zones, such practices could significantly boost sugar beet production and reduce dependency on imported sugar.

Furthermore, consistent application of micronutrients also contributes to environmental sustainability. Foliar fertilization reduces nutrient leaching and runoff compared to soil applications. This is especially important in irrigated farming systems where over-application of fertilizers can cause ecological degradation. By using targeted foliar micronutrient strategies, farmers can enhance fertilizer use efficiency and reduce environmental impact.

The economic implications of this study are also notable. Increased sugar yield and better quality directly enhance profitability for farmers. Cost-benefit analysis indicates that the return on investment from foliar B and Zn applications is significantly higher than standard NPK alone. Future research should evaluate long-term effects across multiple growing seasons and explore interactions with biostimulants and other micronutrients.

Conclusion

This study demonstrates that foliar application of boron and zinc fertilizers particularly in combination and supported by background NPK significantly enhances sugar beet performance. Root yield increased by up to 37 t ha^{-1} over the control, and sugar yield improved by up to 7.1 t ha^{-1}. Bolashak hybrid showed the most pronounced response, making it a strong candidate for large-scale cultivation with optimized nutrition. The use of foliar micronutrients offers a viable agronomic solution for improving yield and sugar content in sugar beet grown under semi-arid conditions. Integrating micronutrient management into standard agronomic practices is essential for achieving sustainable intensification in Kazakhstan's agriculture.

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The Effect of Foliar Zinc Application on Yield Component of Corn Plant

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Abstract

The aim of this study was to determine the effect of foliar zinc (Zn) application on grain yield, Zn content, and Zn uptake of corn (Zea mays L.). In the study, Zn-sulfate fertilizer was applied to corn plants at the 5-leaf stage at rates of control, 0.1%, 0.2%, and 0.4% Zn. The experiment was conducted under a randomized complete block design with 3 replications. At the end of the study, corn grain yield, stalk and grain Zn content, and grain Zn uptake increased significantly ($p < 0.01$) with foliar Zn applications compared to the control. The stalk Zn contents of corn plants were higher than the grain Zn contents in all applications. The highest increases in corn grain yield and stalk Zn content were obtained at the 0.1% Zn dose (28.98%) and at the 0.2% Zn dose (59.60%), respectively, while the highest grain Zn uptake (87.37%) was found at the 0.4% Zn dose. Consequently, based on statistical evaluation, it was recommended that 0.1% foliar application is suitable for increasing grain yield and Zn uptake, while the 0.2% dose is more effective for stalk production in corn plants.

Keywords: Foliar application, zinc, corn, grain yield, content, uptake.

Introduction

Corn (Zea mays L.) is the most important crop in the world after wheat and rice (FAO, 2011). The typical kernel composition of commercial corn, also known as yellow dent corn, is 71.7% starch, 9.5% protein, 4.3% oil, 1.4% ash, and 2.6% sugar (Watson, 2003).

Plant physiologists report that zinc (Zn) exerts a great influence on basic plant life processes: firstly, nitrogen metabolism (nitrogen uptake and protein quality); secondly, photosynthesis (chlorophyll synthesis and maintaining acid–base homeostasis); and thirdly, resistance to biotic and abiotic stress conditions (Alloway, 2004; Cakmak, 2008).

Zinc deficiency often occurs in alkaline soils, light sandy soils, or soils with relatively high levels of available phosphorus (Singh, 2005). Its deficiency causes oxidative damage to biological molecules in plants (Gulcin, 2020), leading to yield reductions of up to 40% (Sadeghzadeh, 2013). Moreover, Zn is highly important for human, poultry, and livestock nutrition (Nuss and Tanumihardjo, 2010).

Corn has long been recognized as highly responsive to Zn and has a high Zn requirement (Subbaiah et al., 2016). Optimum Zn levels in corn tissue range from 20 to 60 ppm (Ivanov et al., 2021). Corn cultivation, particularly in temperate regions, is highly sensitive to environmental and vegetative stresses during early plant development, resulting in reduced grain yields (Leach and Hameleers, 2001; Subedi and Ma, 2009).

Zn fertilization is widely recommended for corn and other cereals to correct deficiencies (Rashid et al., 1979; Tahir, 1981; Khattak and Parveen, 1986; Rashid and Qayyum, 1991). There are three main methods for correcting micronutrient deficiencies: soil application, foliar sprays, and seed treatment. Among these, foliar

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application is one of the most effective and rapid methods (Wilhelm et al., 1988; Savithri et al., 1999; Erenoglu et al., 2002; Grzebisz et al., 2008; Zeb et al., 2022). Repeated foliar Zn applications during the early growth stages are particularly effective.

Kouchak Dezfouli et al. (2024) reported that soil fertilizer use negatively affects microorganisms, reduces soil health, and increases environmental pollution. Therefore, considering sustainable agriculture, foliar fertilization is the best Zn application method to meet plant needs and reduce excessive chemical use. Amanullah et al. (2016) demonstrated that foliar Zn application increases photosynthesis, chlorophyll content, biomass production, and assimilate translocation to reproductive organs, thereby increasing maize seed yield.

Foliar application of Zn, especially in calcareous soils, enhances Zn bioavailability. A 0.1% Zn foliar spray on Zn-deficient corn plants increased grain yield, 1000-grain weight, number of grains per spike, and plant height (Anees et al., 2016).

The aim of this study was to determine the effect of foliar Zn application on grain yield, stalk and grain Zn content, and grain Zn uptake of corn grown on calcareous soils.

Material and Methods

The study was conducted in the Suluova plain of Amasya province in the Central Black Sea region of northern Turkey. The climate is semi-arid, with average annual precipitation of 433.8 mm and evaporation of 870.7 mm. The altitude of the area ranges from 415 to 489 m.

Corn (Zea mays L.) seeds were planted in a 30 m^2 field plot with 0.70 m row spacing. The soil was fertilized with NPK (15:5:6 N:P2O5:K2O kg/da) as the base fertilizer. The experiment was conducted using a randomized block design with 3 replications.

Foliar ZnSO4·7H2O fertilizer (22% Zn) was applied at 0 (control), 0.1%, 0.2%, and 0.4% Zn doses twice a week in the early post-emergence period (5–6 leaf stage). Plants were sprayed until completely wetted, while the control received only tap water.

Corn plants were harvested 140 days after planting (October 7) by cutting them at the soil surface. Grain yield was determined at 15% grain moisture. Plant samples (grain, leaves, and stems) were oven-dried at 65°C and ground (0.2 mm mesh) for analysis.

Zn concentration in stalks (leaf + stem) and grains was determined by atomic absorption spectroscopy (AAS-200) after digestion with HNO3 and HClO4 (4:1 v/v).

Soil analyses included: texture (hydrometer method), pH and EC (saturation paste), lime (calcimeter), available P (NaHCO3), exchangeable K (NH4OAc), organic matter (Walkley–Black), and DTPA-extractable Zn. Some properties of the experimental soil are given in Table 1.

Data were analyzed using SPSS 17.0. Variance analysis was performed, and means were compared by Tukey's test at the 5% probability level.

Table 1. Some properties of the experimental soil

Soil property	Value
pH	8.05
EC, dS/m	1.17
Lime , %	12.65
OM, %	2.28
Textural class	Loamy
Available P, ppm	8.35
Available K, ppm	282
Available Zn, ppm	0.36

Results and Discussion

The Effects of Foliar Zinc Application on Corn Grain Yield

The effects of foliar application on corn grain yield are shown in Table 2. The percentage changes in grain yield of corn plants compared to the control are shown in Table 3. In the experiment, stalk Zn content, grain Zn content, and grain Zn uptake were highly correlated with the applied Zn doses. Variance analysis showed that foliar Zn applications significantly increased corn grain yield compared to the control ($p < 0.01$). A significant ($p < 0.05$) relationship was found between grain yield and foliar applications ($r = 0.681^*$), especially when foliar application at the 0.1% Zn dose was compared to the control (Figure 1). Ceylan et al. (2009) also reported that Zn foliar fertilization increased Zn content as well as crude protein content in alfalfa biomass.

Similarly, Morteza et al. (2023) reported that foliar Zn application increased maize grain yield and grain nutrient content under water-deficit conditions.

Table 2. Effect of foliar Zn application on corn grain yield, stalk and grain Zn contents, and grain Zn uptake

Foliar Zn application, (%)	Grain yield, kg/da	Zn content, ppm		Grain Zn uptake, g/da
		Stalk	Grain	
Control	792c	35.77c	15.00c	11,88c
0.1	**1022a**	82.48b	**21.48ab**	**21,95a**
0.2	912b	**134.9a**	18.45b	16,83b
0.4	930b	131.8a	23.94a	22,26a
Mean	914	105.18	19.72	18.23

Values followed by the same letter are not significantly different at $p < 0.05$ according to Tukey's test.

Table 3. Percentage changes in corn grain yield and Zn components compared to control

Foliar Zn application, (%)	Grain yield kg/da	Zn content, ppm		Grain Zn uptake, g/da
		Stalk	Grain	
Control	-	-	-	-
0.1	29.04	130.58	43.2	86.02
0.2	15.15	277.13	23.0	42.63
0.4	17.42	268.47	59.6	88.64

Zn deficiency in agricultural soils is a major global problem that significantly affects crop yield and nutritional quality (Cakmak, 2008). Maize is highly susceptible to Zn deficiency and absorbs approximately 308 g/ha of Zn in the grain, with about 60% of the Zn taken up by the plant being transported to the grain (Bender et al., 2013). Corn responded well to foliar Zn applications due to the low Zn content (0.36 ppm) of the experimental soil. It is generally accepted that the critical threshold for Zn deficiency is 0.54 mg/kg in soil and 25–100 ppm in leaves (Alloway, 2009). For maize, Zn is the fourth most important yield-limiting nutrient after nitrogen, phosphorus, and potassium (Mutambu et al., 2023). Zn application to maize increases the number and weight of grains, especially in the apical region, due to enhanced photosynthesis and chlorophyll synthesis (Liu et al., 2016; Potarzycki et al., 2016; Xue et al., 2019). Many studies have shown that Zn fertilization significantly increases maize grain yield and Zn content, but optimum soil concentrations and application rates vary with regional climate, soil type, and production system (Zhang et al., 2013; Liu et al., 2017; Butoman et al., 2022; Kumar et al., 2022).

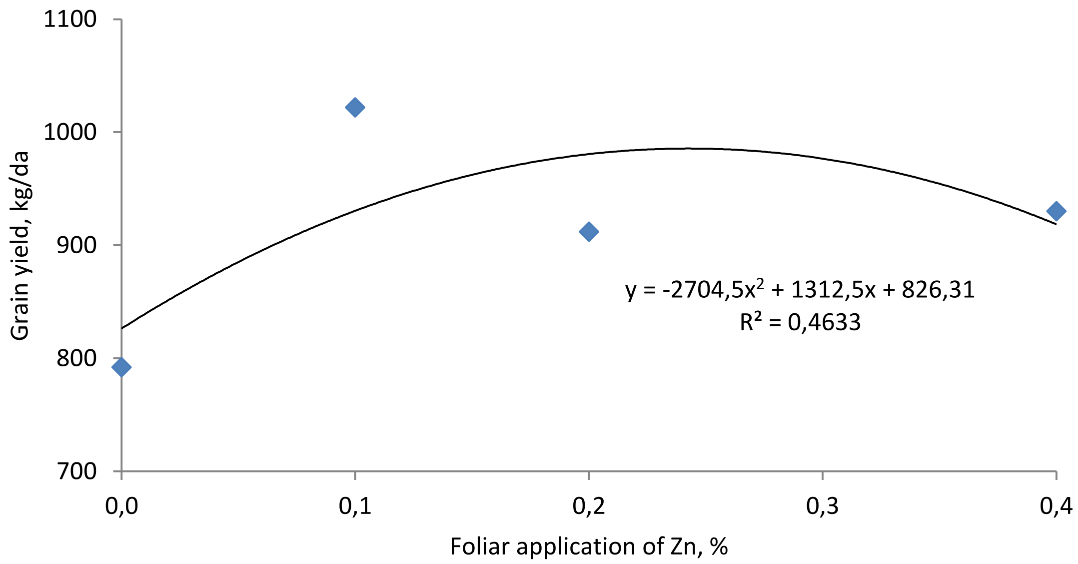


Figure1. Relationship between grain yield and foliar Zn application

The highest corn grain yield was obtained by applying at 0.1% Zn dose (1022 kg/da; 29.04%). Depending on increasing Zn doses, corn grain yield increased at the 0.1% Zn dose and subsequently declined at higher foliar Zn doses, consistent with the law of diminishing returns. Similarly, a significant ($p<0.01$) increase in stalk and grain Zn content was observed as 277.93% at 0.2% Zn application and 59.6% at 0.4% Zn application. Furthermore, grain Zn uptake was also observed as 21.04% increase in 0.1% Zn application (Figure 2). Nutrient use efficiency or percentage change of fertilizer use is an excellent indicator that helps determine the rate at which plants uptake nutrients from the soil and contributes to soil fertility and other soil quality components, thus supporting the sustainability of the agricultural system. Similarly, Botoman et al. (2022) found that applying 3 kg of Zn/ha to the soil increased grain yield by 11% compared to the control.

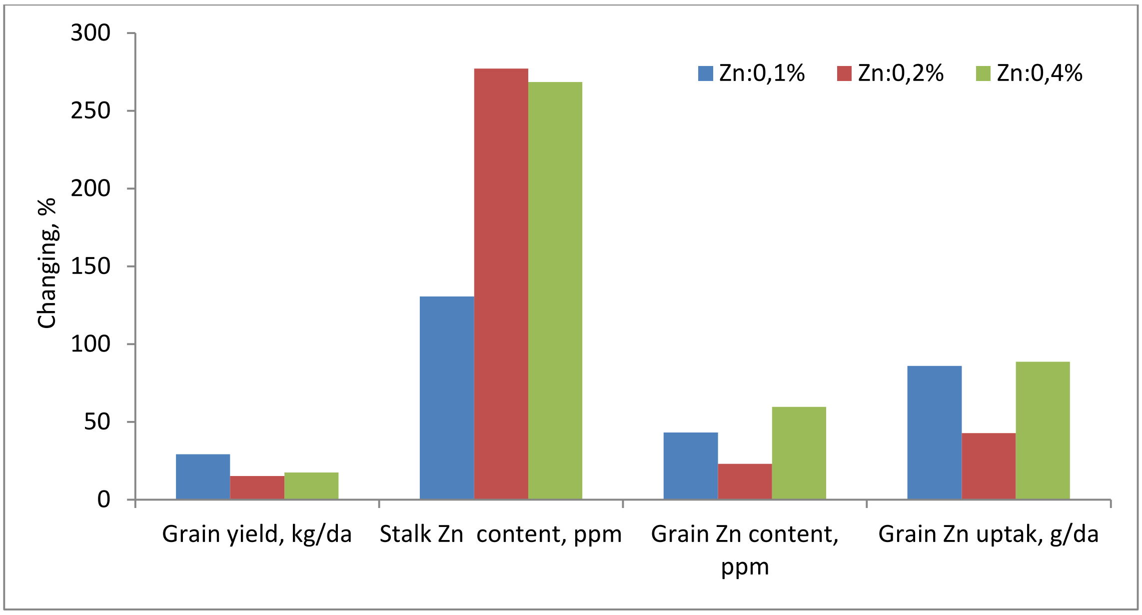


Figure 2. Increase rates of foliar Zn applications on corn grain yield and Zn components

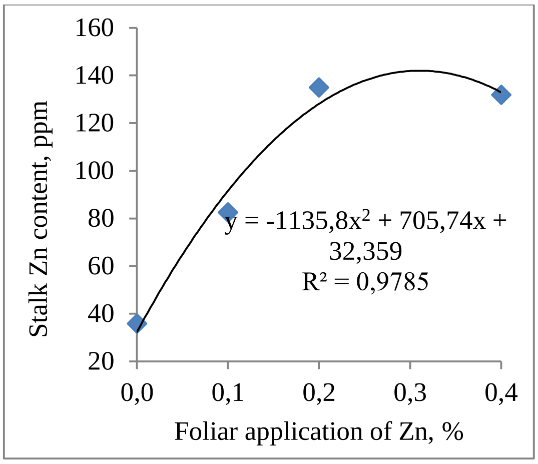
The effects of foliar zinc application on corn zinc components

The effect of foliar applications on corn Zn content (stalk and grain) and grain Zn uptake is shown in Table 2. Foliar Zn application significantly ($p < 0.01$) increased stalk and grain Zn content and grain Zn uptake compared to the control. However, with increasing Zn doses, stalk and grain Zn content and grain Zn uptake decreased linearly (r = 0.979**, r = 0.674*, r = 0.525*; Figure 3).

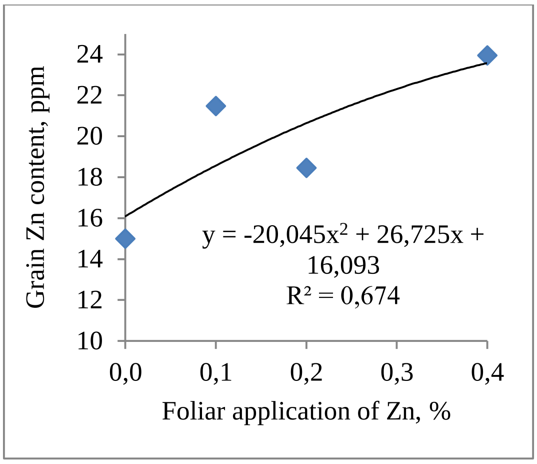
Stalk Zn content (134.90 ppm) increased significantly at the 0.2% Zn dose compared to the control ($p < 0.01$). Although grain Zn content (23.94 ppm) and grain Zn uptake (22.26 g/da) were highest at the 0.4% Zn dose, the 0.1% dose was also statistically significant ($p < 0.01$). Aref (2011) reported that foliar Zn spraying increased leaf Zn from 33 to 48.3 mg kg^{-1} (a 47% increase compared to the non-Zn control), while soil Zn application had no significant effect on leaf Zn. Foliar Zn application is thus a rapid and effective way to correct Zn deficiency (Yılmaz et al., 1997). Galavi et al. (2012) showed that foliar Zn and Mn increased seed Zn and Mn concentrations in safflower. El Samie et al. (2022) reported that foliar application of 180 g Zn/ha significantly increased grain weight.

The highest change in stalk Zn content was at the 0.2% dose (273.13% increase). Grain Zn content (59.6% increase) and grain Zn uptake (88.64% increase) were highest at the 0.4% dose. Yang et al. (2011) reported that foliar Zn applications increased grain Zn concentrations in all tested cultivars by 26–115%, and that combined foliar + soil Zn application resulted in 14% higher grain Zn concentrations than foliar application alone.

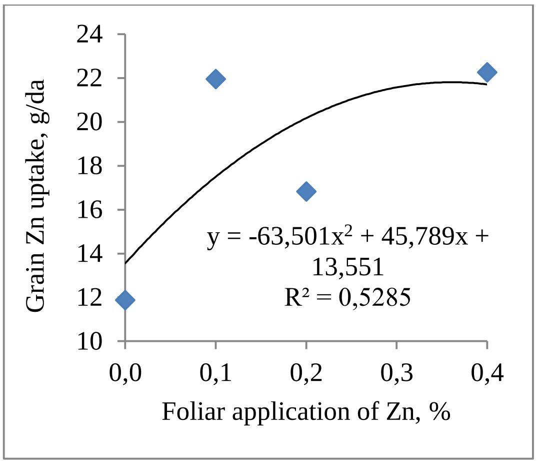
Foliar application at the 0.1% Zn dose was determined to be the most effective for both grain yield and Zn components. Subedi and Ma (2009) estimated that the attainable yield reduction due to lack of Zn application was about 10%. Wang et al. (2012) emphasized that grain Zn uptake is a more effective indicator than concentration alone because it reflects bioavailability for both plants and humans. Foliar Zn application achieved higher grain Zn recoveries of 35.2% and 42.9% in corn compared to soil Zn application. Thus, foliar application is more effective than soil Zn application in improving grain Zn recovery. Nutrient use efficiency remains a critically important concept in evaluating crop production systems (Fixen et al., 2015).



a) Stalk Zn content



b) Grain Zn content



c) Grain Zn uptake

Figure 3. Effects of foliar Zn application on corn plant stalk Zn content, grain Zn content, and grain Zn uptake

Conclusion

In this study, the 0.1% foliar Zn dose produced the highest values, with a grain yield of 1022 kg/da, a grain Zn content of 21.48 ppm, and a grain Zn uptake of 21.95 g/da. At this dose, grain yield, grain Zn content, and grain Zn uptake increased by 29.04%, 43.20%, and 86.02%, respectively, compared with the control. In contrast, the greatest increase in stalk Zn content (277.33%) was observed at the 0.2% Zn dose. These results indicate that Zn use efficiency in maize can be improved by enhancing Zn bioavailability, thereby contributing both to human nutrition (through grain consumption) and to animal nutrition (through silage). Accordingly, a 0.1% Zn foliar dose is recommended for maximizing grain yield and nutritional quality, while a 0.2% Zn foliar dose is more suitable for increasing stalk production for silage purposes.

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Calibration of Soil Analysis Method for Fertilization: for Example Organic Matter

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Abstract

This study examined how chemical analysis methods used to determine soil nutrient levels are calibrated and how fertilizer recommendations are made based on these levels, using organic matter (OM) as an example. Calibration studies allow chemical methods used in soil analysis to be tested under field conditions for each crop (or indicator plant) according to the regional climate and soil characteristics. They also provide the basis for defining soil sufficiency levels (very low, low, medium, high, very high, and excessive) and calculating the fertilizer rates to be applied. In a calibration study, soils are first grouped according to their nutrient or OM levels as very low, low, medium, high, or very high. Plants are then grown in field trials with increasing fertilizer rates according to the nutrient content of each soil (1.39–4.26% OM). Parabolic multiple regression equations are developed to relate the relative yield values of the test plants to soil nutrient content and fertilizer doses. Based on these equations, soils are classified by calculating the fertilizer dose required to achieve 95% of the maximum yield. As a result, soils were classified by their OM content: very low (<1.39% OM), low (1.39–2.91% OM), medium (2.92–3.61% OM), high (3.62–4.22% OM), and very high (>4.22% OM). Corresponding nitrogen fertilizer requirements were 20, 15, 10, and 5–0 kg N/da, respectively, while no fertilizer was recommended for soils with very high OM content. In conclusion, to obtain accurate and reliable fertilizer recommendations, chemical analysis methods must be calibrated according to local climate and soil conditions before being applied in practice.

Keywords: Calibration, soil, nutrient levels, classification, fertilization.

Introduction

The mathematical relationships between plant nutrients (or organic matter) in the soil and crop yield were first formulated by Mitscherlich (1912), and later a similar equation was developed by Spillmann (1980):

(logA-y)=LogA-c(x+b)

Subsequently, the modification of the Mitscherlich equation for agricultural practices, which also considered the influence value of nutrients already present in the soil (c_1), was carried out by Bray (1944) and Aktaş (1994):

(logA-y)=LogA-cx-c1b

In these formulas:

A = maximum yield

y = yield obtained from the nutrients present in the soil

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x = nutrient added to the soil (fertilizer applied)

c = impact factor or influence value of the nutrient supplied by fertilizer

b = amount of nutrient present in the soil (determined by soil analysis)

c1 = impact factor or influence value of the relevant nutrient present in the soil

These studies paved the way for significant advances in the calibration of soil analysis. In particular, the calibration of phosphorus (P) and potassium (K) analysis methods was first initiated by Mitscherlich and later modified by Bray in the form of the "modified Mitscherlich equation," which became widely used and achieved successful results. In Türkiye, several methods used in phosphorus and potassium analyses were calibrated based on this equation, and the required fertilizer doses were determined according to soil needs for these nutrients (Yurtsever & Akalan, 1975; Yurtsever, 1978; Arslan, 1989; Özdemir, 1989).

Laboratory, greenhouse, and field experiments are commonly used to determine plant-available nutrients such as nitrogen, phosphorus, and potassium. Although the fundamental purpose of greenhouse and field experiments is the same, their application methods differ. Field experiments are carried out under natural environmental conditions, while greenhouse experiments are conducted under controlled conditions, usually in pots. For example, under field conditions, soil nitrogen requirements are determined by comparing yields from fertilized and unfertilized plots. In greenhouse trials, increasing doses of nitrogen fertilizer are applied, and plant-available nitrogen levels are estimated based on yield response. However, both approaches require more time to obtain results compared with chemical analysis methods (Horuz, 2002). Currently, numerous chemical analysis methods are used in laboratories to determine plant-available nitrogen. However, no single method can be considered universally reliable for regions with diverse climatic and soil conditions. A method effective in one area may not be compatible with soils in another. Therefore, it is essential to test analysis methods across different regions, compare them with standard reference methods, identify the most accurate, and calibrate them for different crops accordingly (Özdemir, 1989; Horuz, 2002). Purvis and Leo (1961), Kacar et al. (1973), and Ryan et al. (1971) reported that organic matter (OM) methods may be among the most suitable for determining plant-available nitrogen.

In this study, chemical methods used to evaluate soil analysis results and to recommend fertilization were calibrated by growing plants under regional soil and climate conditions, using organic matter as an example. At the end of the study, soils were classified according to their organic matter content, from very low to very high, and the required nitrogen fertilizer amounts were determined based on the soil's OM content.

Calibration of Chemical Methods

The primary aim of calibrating soil analysis methods is to classify soils according to their nutrient content and, accordingly, to determine the optimum fertilizer dose, derived either from the maximum yield or the most economical yield, to be applied to plants. To achieve this goal, parabolic multiple regression equations are used to define the relationships among available nutrient levels (x_1), as determined by chemical analyses, applied fertilizer doses (x_2), and the resulting relative crop yield (y). This relationship is generally expressed in the following form:

$$y = a + bx_1 + cx_2 + dx_1^2 + ex_2^2 + fx_1 \cdot x_2$$

Using such equations, relative crop yields corresponding to different fertilizer doses can be calculated by taking into account the nutrient levels of the soils in the region where the experiment is conducted. In this way, the plant's response to fertilizer in soils where no experiments have been established can also be estimated through calculations. The relative grain yields obtained from control plots are expected to be highly correlated with the nutrient content (or OM) of the soils (Rodriguez et al., 1989). In the soils to be tested, the yield obtained without fertilizer application (from the nutrients already present in the soil) should vary widely as a percentage of the maximum yield. This variability increases the reliability of the calibration study. Several researchers have also reported that predicting the fertilizer requirement of a crop is more reliable when tested under a wide range of soil conditions (Varvel et al., 1981; Enwezor, 1977; Fiedler et al., 1987). Therefore, experimental sites should include not only highly responsive soils, but also soils with very low, medium, and very high responsiveness. In general, as soil test values increase—that is, as the nutrient level in the soil rises—the amount of additional fertilizer required to sustain yield decreases (Culman, 2021). Horuz (2002) reported that the parabolic relationship between soil organic matter levels (x_1), applied nitrogen doses (x_2), and the resulting relative grain yield (y) was significant at the 1% level (Figure 1).

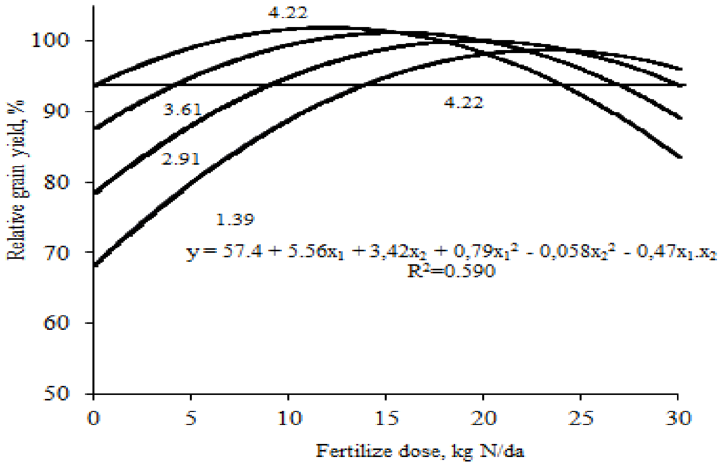

Figure 1. Effect of applied nitrogen (N) doses on relative grain yield in corn plants under different soil organic matter (OM) contents (1.39, 2.91, 3.61, and 4.22%) (Horuz, 2002).

Using this equation, the actual relative grain yield (y) values obtained by applying 0, 5, 10, 15, 20 and 25 kg N/da nitrogen doses in the experimental soils with organic matter contents ranging from 1.32% to 4.92% were calculated.

$$Relative\ grain\ yield = \frac{Grain\ yield\ obtained\ N\ dose,\ kg\ da^{-1}}{Grain\ yield\ obtained\ optimum\ N\ dose,\ kg\ da^{-1}} x100$$

Then, the relative grain yield values for different locations were calculated based on increasing nitrogen doses. The deviations between the observed relative grain yield values in the experiments and the calculated values should be low (<10%) (Rodriguez et al., 1989).

Deviation = Relative yield observed in the experiment – Relative yield calculated.

In addition, the relative error values for the "y" values obtained from the calibration equation for organic matter were calculated using the following formula (Weber, 1972):

$$Relative\ Error = \frac{|y - y^*|}{y^*} x100$$

In this equation, y represents the relative yield values obtained experimentally, and y* represents the relative yield values calculated from the equation:

$y=57.4+5.56x_1+3.42x_2+0.79x_1^2-0.0585x_2^2-0.470x_1.x_2$

Accordingly, the organic matter method was found to be suitable for calibration of the local soils, since the average relative error value calculated from the above equation (R^2 = 0.590) was below 10% (6.86%). Using this equation, the pure nitrogen (N) requirement to achieve 95% of the maximum relative yield was calculated for soils with different OM levels, depending on increasing nitrogen doses (x_2), provided that the OM content of the regional soils (x_1) remained within the experimental range. These values are presented in Table 1. Through this calibration approach, plant responses to nitrogen fertilization in untested soils can also be estimated by applying the multiple regression equation developed from the experimental data. Thus, both the required nitrogen fertilizer rate and the soil's sufficiency class can be reliably determined based on OM content (Carefoot et al., 1989; Horuz & Korkmaz, 2004).

Table 1. Nitrogen fertilizer requirements and sufficiency classes according to soil organic matter content (Horuz, 2002).

Soil OM content (%)	Fertilizer requirement, (N kg/da)	Soil sufficiency class
x < 1.39	20	Very low
1.39 – 2.91	15	Low
2.92 – 3.61	10	Moderate
3.62 – 4.22	0-5	High
4.22 < x	0	Very high

OM: Organic matter

Consequently, since each plant's nutrient uptake potential varies under different soil and climatic conditions, its response to fertilization also differs. Therefore, soil analysis methods should be calibrated through field experiments using indicator crops (such as corn) or other representative plants grown under regional soil and climate conditions. Parabolic multiple regression equations should be employed to define the relationship between soil nutrient levels (or OM content) and the relative yields obtained at increasing fertilizer doses. Based on these relationships, soils should be classified into sufficiency levels (very low, low, moderate, high, and very high). Accordingly, fertilization programs should be designed so that soils with low nutrient content receive higher fertilizer inputs, whereas soils with high nutrient content require little or no additional fertilizer.

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Temporal Changes in Soil Physical Quality Parameters From 2005 to 2020 in Tekkeköy, Samsun, Türkiye

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Abstract

Soil is a dynamic structure that constantly changes in terms of physical, chemical and biological properties. Continuous monitoring of these changes that may occur provides important information in terms of understanding the soil structure. In this study, changes in some soil physical quality parameters in agricultural areas in Tekkeköy district of Samsun province between 2005 and 2020 were examined. Within the scope of the study, pH, EC, Lime, Soil Texture, Bulk Density, Organic Matter, Soil Erodibility, Soil Crust Factor and Soil Compaction analyzes were carried out in 38 soil samples taken from agricultural areas between 2005 and 2020. In the analysis, it was observed that there were statistically significant changes at the level of 5% in Soil Crust Factor, Soil Compaction, EC and Silt data between 2005 and 2020. When it is considered that the soil samples cover agricultural areas, it can be seen because of intensive agricultural practices over a 15-year period. In addition, when the pH, Sand, Clay and Bulk Density data are examined, it is expected that no statistical change has been seen. As a result of the study, it is an important data that the changes in soil physical quality parameters have been revealed due to the intensive agricultural practices that agricultural soils have been exposed to over the years.

Keywords: Soil erodibility, soil crust factor, soil compaction, organic matter, Tekkeköy.

Introduction

Soil is a dynamic structure that undergoes constant change, directly or indirectly, sometimes in seconds or over centuries, under the influence of physical, chemical and various biological external factors (IPCC, 2019; Meurer, 2020). Furthermore, it has been observed that long-term changes in soil management practices or climate, under the influence of external factors, cause deterioration in the soil-plant ecosystem, that is, the physical properties of the soil, and that these factors trigger changes in soil structure (Blanchy et al., 2023; Gregory et al., 2015). Studies indicate that the physical structures of the majority of soils worldwide are very poor, poor, or only in fair condition (FAO/ITPS, 2015), and that unless measures are taken, the effects of this will be even worse because of climate change and increasing pressure on the soils (IPBES, 2018; IPCC, 2019).

Land degradation and soil loss as a result of intensive land use (Sanderman et al., 2017) not only increases the amount of atmospheric CO2 but also cause a decrease in the physical quality and productivity of soils (Lal, 2007; Henryson et al., 2018). Land degradation can be affected by changes that may occur because of human-induced practices and climatic conditions, but soil properties, the geomorphological structure of the area and topographic differences determine the vulnerability levels of the areas (Petrosillo, 2023). It is important to

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determine the physical quality of soils to best determine sustainable land management and the degree of land degradation (Roldan et al., 2003).

The study aimed to examine changes in soil physical quality indicators using samples taken from agricultural soils in two different periods between 2005 and 2020 in Tekkeköy, Samsun, Türkiye. To determine the physical quality of the soil, analyses of pH, EC, lime, soil texture, bulk density, organic matter, soil erodibility, soil crust factor, and soil compaction were evaluated.

Material and Methods

Description of The Study Area

This study was conducted in an area within the Tekkeköy district of Samsun province, encompassing approximately 13 micro-catchments and totaling approximately 226 km2 of study area (Figure 1). The 2020 land use distribution of the study area reveals that agriculture, forest, and pasture account for approximately 39%, 25%, and 30%, respectively. The area is characteristically located in the central Black Sea climate zone, characterized by high summer temperatures and a humid ecosystem. The hottest and coldest months are August and January, respectively (MGM, 2025).

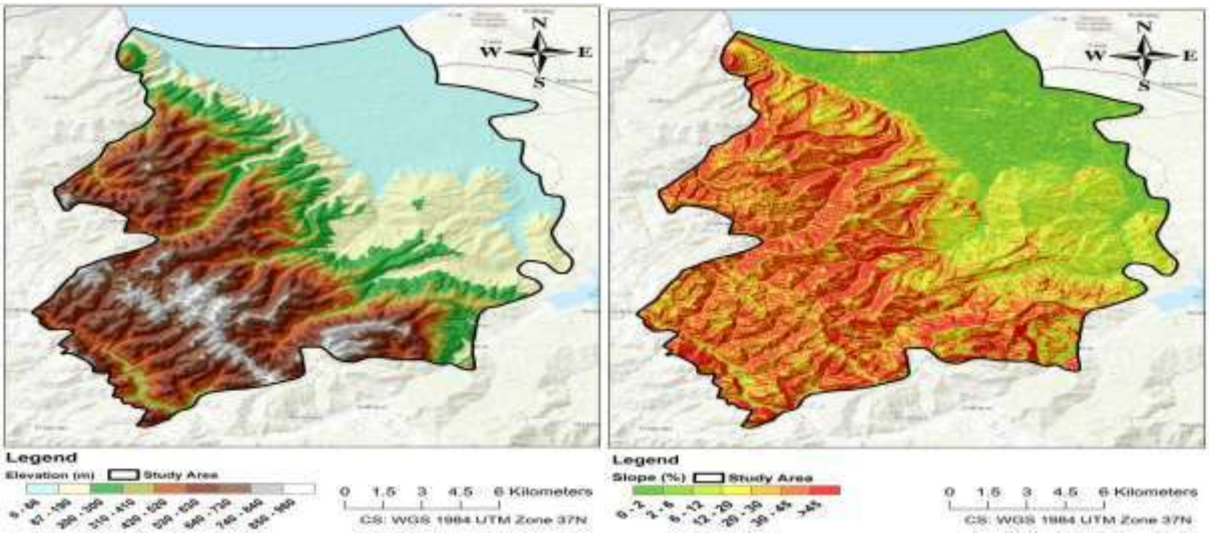

Figure 1. Elevation and slope maps of the study area

Soil Sampling and Analysis

For the study, 38 soil samples taken from agricultural areas in 2005 were used as the reference data set (Figure 2). The soil samples taken for this purpose ranged from 0 to 30 cm in depth, and pH (Methods of Soil Analysis, 1982), EC (Methods of Soil Analysis, 1982), lime (Soil Survey Staff, 1993), organic matter (Jackson, 1958), texture (Demiralay, 1993), and bulk density (Blake and Harthe, 1986) were analyzed. Furthermore, the study presents a comparison of the soil characteristics of the 2005 soil data set, which includes soil samples taken in 2020 from similar study areas. The soil samples used for both periods represent agricultural areas, and care was taken to ensure they were similar to each other.

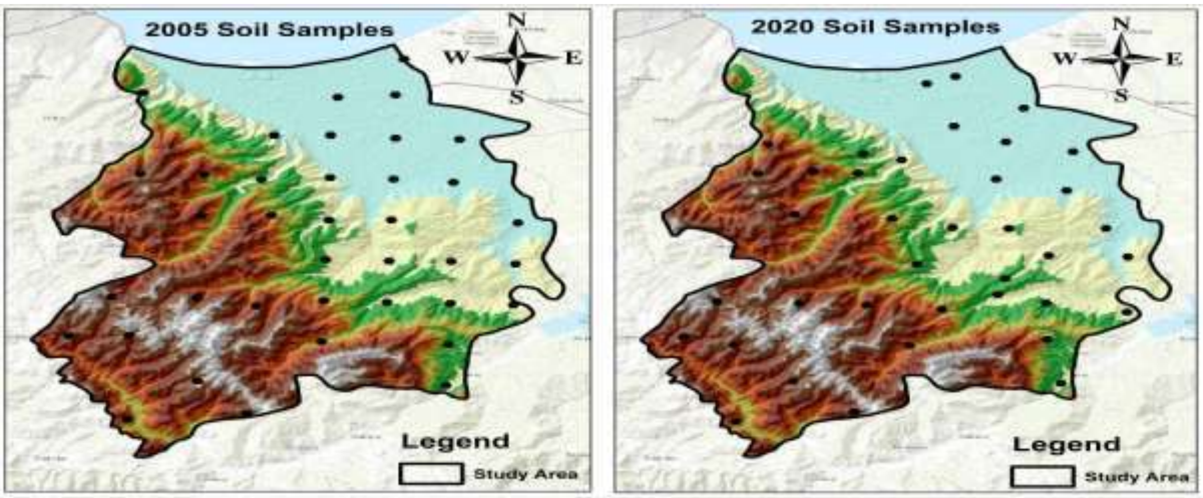

Figure 2. The location of study area and sampling points.

Soil Compaction Susceptibility

Soil compaction is a process that occurs with the decrease of porosity in the physical structure of the soil and causes structural deterioration by causing changes in temperature and moisture regimes (Soane and van Ouwerkerk, 1994). To determine the susceptibility of soils to compaction, the index developed by Vignozzi et al. (2007) was used. The formula used in the study is;

$$\rho 100_{kPa}=1.04231+\exp(-0.486474-0.464448186*SOC)$$

$$CI= -0.09266+0.01576*(Si+Cl)-0.00012*(Si+Cl)^2+\rho 100_{kPa}$$

SOC - soil organic carbon (%), Si – silt (2–50 μm) (%), Cl - clay (< 2 μm) (%)

Soil Crusting Susceptibility

Crust formation, which is considered one of the most important physical problems for agricultural soils, can be defined as the process of deterioration of the structure of aggregates on the soil surface as a result of raindrops hitting them and subsequent drying processes (Chen et al., 1980; Valentin and Bresson, 1997). To calculate soil crust index, the formula below is used (Pierri, 1989);

Soil Crust Index = (Organic matter (%) x 100) / (Clay (%) + Silt (%))

Classes of the Soil Crust Index: CFI < 5 High physical degradation, 5< CFI < 7 Moderate physical degradation, 7<CFI<9 Low physical degradation, CFI > 9 No physical degradation.

Soil Erodibility (K)

Determining the susceptibility of soils to erosion is crucial for estimating soil loss and for environmental assessments. The following formula, developed by Wischmeier and Smith (1978), is used to estimate soil erosion:

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

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.

Statistical Analysis

Within the scope of the study, a paired samples t-test approach was used to determine whether there were significant differences between the two periods in determining the temporal changes in the samples taken between 2005 and 2020. IBM SPSS Statistics 21 package program was used for statistical analyses and ArcMap 10.5 program was used for maps.

Results and Discussion

This study examined the temporal distribution and changes in soil samples taken from agricultural areas during two different periods. Soil properties such as pH, EC, lime, soil texture, bulk density, organic matter, soil erodibility, soil crust factor, and soil compaction were investigated. A total of 38 surface soil samples taken from agricultural areas for both periods were evaluated. The variance values for each parameter were evaluated according to Wilding's (1985) classification system. Here, as stated in the classification system, values for soil erodibility, soil crust factor, soil compaction, pH, EC, om, and bulk density are shown to have low variance at values less than 15%, while Lime values with 15.50% have a medium variance, and silt, clay, and sand with values greater than 35% have a high variance of 38.56%, 226.22%, and 321.93%, respectively (Table 1). Among the parameters we consider important within the scope of the study, the average values for soil erodibility, soil crust factor, and soil compaction were calculated as 0.2, 3.31, and 1.78, respectively. Wang et al. (2019) stated that the characteristics of surface soils significantly affect soil erodibility. They noted that erodibility increases with bulk density but decreases with organic matter, surface crust, root density, and plant residues.

When the results of the soil analysis and calculated indices for the 2020 data are examined within the scope of the study, it is seen that the moderate variance in the lime content of the soils compared to 2005 had a high degree of variance in 2020, at 39.32% (Table 2). Furthermore, the silt, sand, and clay contents also had high variances, at 43.90%, 277.39%, and 409.86%, respectively. When the texture contents of the soils for both periods are examined, it is revealed that they have an average clayey structure. In Europe, sampling studies are conducted regularly and comprehensively at regular intervals to examine changes in soils over time. These studies examine not only the biological properties of soils but also physical parameters such as erosion

(Orgiazzi et al., 2018). Similarly, in studies where soil properties are monitored through repeated measurements, the USGS conducts sampling at 53 different locations over 7-year periods (McHale et al., 2014).

Table 1. Descriptive statistic of soil samples taken from 2005.

Parameters	Mean	Minimum	Maximum	Std. Deviation	Variance	Skewness	Kurtosis
Soil Erodobility	0.20	0.02	0.26	0.05	0.00	-1.80	3.97
Soil Crust Factor	3.31	0.89	10.73	1.87	3.50	2.31	7.06
Soil Compaction	1.78	1.56	1.99	0.09	0.01	-0.08	0.26
pH	6.80	5.08	7.70	0.65	0.43	-0.53	-0.49
Electrical Conductivity	0.39	0.20	0.60	0.10	0.01	0.18	-0.74
Lime	2.42	0.16	17.78	3.94	15.50	2.42	5.99
Organic Matter	2.11	0.48	4.00	0.78	0.61	0.13	-0.12
Sand	30.66	6.31	79.54	17.94	321.93	1.01	0.61
Silt	28.37	4.14	36.34	6.21	38.56	-2.01	5.86
Clay	40.97	8.87	69.54	15.04	226.22	-0.29	-0.53
Bulk Density	1.38	1.21	1.57	0.10	0.01	0.27	-0.91

Table 2. Descriptive statistic of soil samples taken from 2020.

Parameters	Mean	Minimum	Maximum	Std. Deviation	Variance	Skewness	Kurtosis
Soil Erodibility	0.18	0.01	0.25	0.06	0.00	-1.29	0.94
Soil Crust Factor	4.40	1.06	10.03	2.54	6.44	0.89	-0.22
Soil Compaction	1.74	1.54	1.94	0.11	0.01	0.06	-0.49
pH	6.87	5.22	8.05	0.76	0.57	-0.32	-0.83
Electrical Conductivity	0.29	0.07	0.79	0.15	0.02	0.99	1.59
Lime	3.58	0.48	28.40	6.27	39.32	2.57	6.59
Organic Matter	2.70	0.75	6.47	1.42	2.01	0.98	0.82
Sand	32.65	4.95	89.32	20.25	409.86	1.00	0.39
Silt	25.49	0.94	40.33	6.63	43.90	-1.16	4.35
Clay	41.86	9.74	66.37	16.65	277.39	-0.52	-0.93
Bulk Density	1.35	1.18	1.58	0.11	0.01	0.58	-0.44

A region with intense agricultural production was selected for the study, and changes between 2005 and 2020 were demonstrated. Here, temporal changes in the data were examined, and the significance of these temporal changes was determined. Within the scope of the study, it can be said that the soil crust factor, soil compaction, EC, om, and silt parameters showed significant temporal changes between 2005 and 2020, and these values were within the 95% confidence interval ($p<0.05$). A slight decreasing trend in soil crust factor was observed in 2020 compared to 2005. Furthermore, when examined in terms of soil compaction, soils showed a slight increasing trend compared to 2005 due to intensive agricultural practices and mechanization, and this was significant at the 5% level (Table 3). When the soils were evaluated in terms of pH, lime, sand, clay, and bulk density, no significant change was observed over time. Agricultural practices are significantly affected by management practices and vegetation cover, as well as erosion. Therefore, determining soil erodibility will create an important data set for soil conservation measures (Panagos et al., 2014).

Table 3. Paired samples t test results between 2005 and 2020.

Parameters	Paired Differences			t	df	Sig. (2-tailed)
	Mean	Std. Deviation	Std. Error Mean			
Soil Erodobility	0.02	0.06	0.01	1.94	37.00	0.06
Soil Crust Factor	-1.09	2.91	0.47	-2.31	37.00	0.03
Soil Compaction	0.05	0.13	0.02	2.26	37.00	0.03
pH	-0.07	0.83	0.14	-0.50	37.00	0.62
Electrical Conductivity	0.10	0.17	0.03	3.69	37.00	0.00
Lime	-1.16	7.29	1.18	-0.98	37.00	0.33
Organic Matter	-0.59	1.51	0.25	-2.41	37.00	0.02
Sand	-1.99	23.15	3.75	-0.53	37.00	0.60
Silt	2.89	8.73	1.42	2.04	37.00	0.05
Clay	-0.89	19.38	3.14	-0.28	37.00	0.78
Bulk Density	0.02	0.15	0.02	1.00	37.00	0.32

As part of the study, we created distribution maps for soil erosion susceptibility, soil crust formation, and soil compaction susceptibility, which we consider particularly important for both periods analyzed. It is essential to illustrate the distribution of soil data for these periods and to identify sensitive areas. When assessing soil erosion susceptibility, areas with lower erodibility values are regarded as more resistant, while soils with higher values are more susceptible to erosion (Renard et al., 1978). When comparing the data, it is evident that soil erodibility has significantly increased since 2005. One of the most notable physical damages observed is soil crusting, which occurs due to the destruction of soil structure by raindrops followed by the drying of the soil (Demirağ Turan and Dengiz, 2021).

A statistical analysis of soil crust formation values indicates a significant difference between the averages, showing a decrease in 2020 compared to the previous period. Soil crust factor values below 5 suggest that the soil may be more susceptible to degradation. İmamoğlu et al. (2018) found a significant 95% correlation between soil crust formation and soil texture. Their study revealed that while higher sand and silt contents positively influenced crust formation, there was a negative correlation with clay content. When examining these results alongside distribution maps, a decline in vulnerable areas is also evident. An examination of soil sensitivity to compaction reveals a slight increase in sensitive areas in 2020. The distribution of these sensitive areas reveals an increase in the northeastern regions, where agricultural production is concentrated. Intensive tillage and agricultural production increase soil sensitivity to compaction. Kara et al. (2023) report that the use of conservative tillage methods improves soil properties such as bulk density, porosity, and penetration resistance, providing a suitable environment for plant growth.

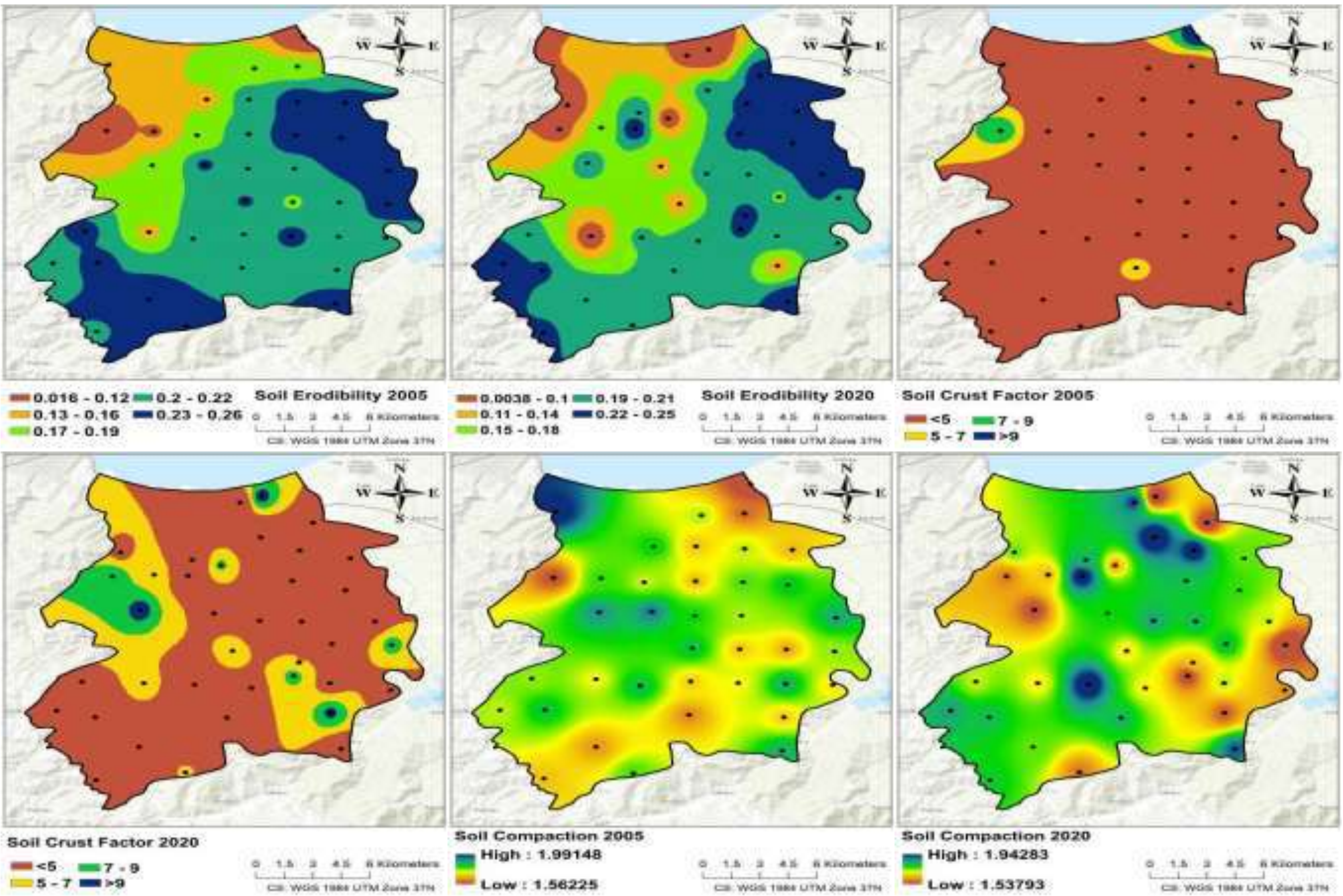

Figure 3. Soil erodibility, soil crust factor and soil compaction distribution maps

Conclusion

Soil is a dynamic structure that constantly changes in terms of physical, chemical and biological properties. Continuous monitoring of these changes that may occur provides important information in terms of understanding the soil structure. In this perspective, in order to reveal the long-term changes in agricultural soils, temporal changes in soil properties were revealed with samples taken from agricultural soils in Tekkeköy district of Samsun province between 2005 and 2020.

The study found significant changes in soil crust, soil compaction, EC, silt, and organic matter parameters between 2005 and 2020. Soil erodibility, pH, lime, sand, clay, and bulk density parameters did not show significant changes between years. Consequently, the study concludes that these changes are due to practices such as intensive tillage and soil cultivation occurring on agricultural soils.

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Effects of Topographic Variability and Different Land Cover on Soil Development and Catalase Enzyme Activity

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Abstract

Soil microorganisms form the basis of the biological components of the soil ecosystem. These microorganisms produce various enzymes during their vital activities and ensure that biochemical processes in the soil are carried out. The aim of this study is to reveal the development of soils formed on basaltic parent material located at different land covers and different elevations and to investigate the change in catalase enzyme activity. This study was carried out in the Engiz basin located in the south of Bafra district within the borders of Samsun province. The soils were classified as Typic Haplustert and Lithic Ustorthent and catalase enzyme activity was evaluated in order to reveal the biological properties of the soils in the study area. Four profiles were opened along the determined line in the southwest-northeast direction and it was founded that the catalase enzyme activity of the soil samples taken from the opened profiles varied between 14.175-325.800 µl O2 g-1 dry soil. In addition, when the statistical relationship between catalase enzyme activity and different profiles, land cover and elevation was examined, it was determined that the effect of different profiles and different elevations on catalase enzyme activity in the soil was significant at the %1 level ($P=0.000<0.01$), while the effect of different land cover types on catalase enzyme activity in the soil was insignificant ($P=0.886>0.05$).

Keywords: Catalase enzyme activity, microorganism, soil biological properties, soil fertility, soil formation.

Introduction

Soil is not only a physical and chemical entity, but also a dynamic and living system in which various biological processes continuously take place. One of the smallest but most effective components of this ecosystem are soil microorganisms. Soil microorganisms play a vital role in soil fertility, structural integrity and ecological functionality (Sylvia et al. 2005). Therefore, microorganisms, which are among the most important members of the soil biota, play a critical role in the sustainability of ecosystems (van der Heijden et al. 2008; FAO, 2020). Therefore, soil microorganisms are of great importance for soil health and productivity in both natural ecosystems and agricultural production.

Soil microorganisms decompose organic wastes and provide the biological cycle of essential elements such as carbon (C), nitrogen (N), phosphorus (P) and sulfur (S). Macro and microorganisms within the soil ecosystem play essential roles not only in the decomposition of organic matter but also in the weathering processes of minerals and rocks. These organisms accelerate the dissolution of rock minerals through mechanical destruction and biochemical reactions, thus directly contributing to soil formation processes (Brady and Weil, 2016; Bardgett and van der Putten, 2014). In addition, polysaccharides, proteins and other binding substances

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produced by microorganisms enable soil particles to form aggregates, which positively affects soil physical properties such as water permeability, air capacity and erosion resistance (Zhang et al. 2024). These cycles ensure the sustainable recovery of plant nutrients in ecosystems (Paul, 2014). At the same time, it improves the structure and nutrient retention capacity of the soil by supporting humus formation (Six et al. 2004; Lavelle and Spain, 2001).

Another basic function undertaken by soil microorganisms is the synthesis of various enzymes. These enzymes play a central role in regulating and conducting biochemical reactions in the soil ecosystem. Enzyme activities in soil are critical indicators for the decomposition of organic matter, the transformation of nutrients and monitoring of microbial activity (Nannipieri et al. 2002). Catalase enzyme is directly associated with the aerobic respiration processes of microorganisms and is considered an important bioindicator in determining biological viability and microbial metabolic activity in soil (Pan et al. 2023). Catalase enzyme catalyzes the decomposition of hydrogen peroxide (H_2O_2) into water and molecular oxygen. Catalase enzyme acts as an intracellular enzyme that reflects the metabolic activity of aerobic microorganisms, which is closely related to the presence of aerobic microbial population in the soil and soil fertility (Bach et al. 2010). The physical properties, chemical components and biological factors of soils are among the main factors that significantly affect catalase activity (Ekberli and Kızılkaya, 2006; Kızılkaya and Hepşen, 2007). In addition, pollutants such as heavy metals reaching the soil and agricultural interventions such as pesticide applications also lead to significant changes in catalase enzyme activity (Kızılkaya et al. 2004; Burns et al. 2013).

Enzymatic activities in the soil support soil profile development by accelerating the transformation of organic and inorganic matter, which is one of the basic components of soil formation (Burns et al. 2013). Therefore, soil enzyme activities are one of the main indicators representing the biological aspect of soil formation processes and are critical for the sustainability of soil health and productivity (Sinsabaugh and Follstad Shah, 2012). The aim of this study was to determine the relationships between catalase enzyme activity of soils formed on basaltic parent material and elevation and land cover and to reveal the effects of these parameters on soil formation.

Material and Methods

General Description of the Research Area

The Engiz basin is located in the Central Black Sea Region, north of the Bafra Plain, within the borders of Samsun province. The study area is located within the Dağköy area of the Engiz basin, in the Southwest-Northeast direction and with an elevation ranging from 20 m to 300 m above sea level (Figure 1).

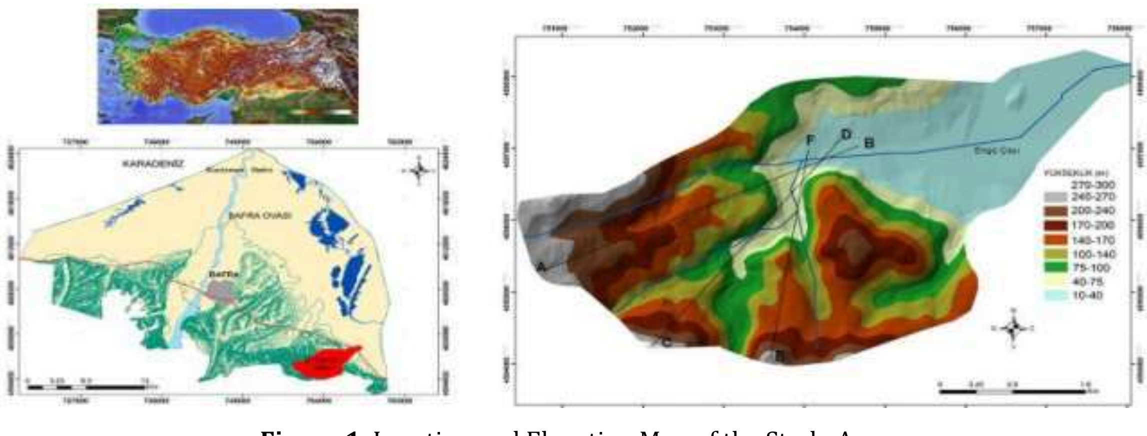

Figure 1. Location and Elevation Map of the Study Area

The largest unit outcropping in the study area and its immediate surroundings is the Yenikonak formation. The volcano consists of sedimentary rocks. The majority of it consists of tuff, tuffite, basalt, sandy limestone and marl intercalations of sandstone-shale. The soils formed on the basalt parent material in the study area include pasture areas and areas where dry farming is done, and although very few, there are forested areas consisting of oaks. Average temperatures are below 10°C in four months of the year (December, January, February, March), but begin to rise starting from April. The average annual precipitation in the study area is around 800 mm, with the majority of rainfall occurring in winter.

Four profiles were opened on the Southwest-Northeast (CD) section and disturbed and undisturbed soil samples were taken from each profile hole based on the horizon. The soil samples brought to the laboratory were dried, sieved through a 2 mm sieve, and stored in plastic storage containers to be used in analyses. Physical, chemical, biological, morphological, mineralogical and geochemical analyses were carried out on the soils prepared for analysis. Each profile opened for the morphological description of the soils was examined based on the methods specified by the Soil Survey Staff (1993). The definition and naming of horizons were made according to Soil Survey Staff (1999).

Physical and Chemical Analyses

Texture was determined in disturbed soil samples by Bouyoucos (1951), cation exchange capacity was determined by Rhoades (1986) using 1 N ammonium acetate (NH_4OAc) adjusted to pH 8.2, Exchangeable cations (Na and K) were determined by Rhoades (1986) using ammonium acetate (NH_4OAc) adjusted to pH 8.2, and Ca+Mg was determined by the difference between the cation exchange capacity and total exchangeable sodium and potassium. $CaCO_3$ was determined by using a Scheibler calcimeter for the determination of free carbonates as reported by the Soil Survey Staff (1993), soil reaction (pH) and electrical conductivity were determined by using a pH meter and a conductivity meter for saturation mud as reported by the Soil Survey Laboratory (1992; 2004), and organic matter was determined by using the Walkley-Black method as modified by Jackson (1958).

Catalase Enzyme Activity

Catalase enzyme activity (EC 1.11.1.6) of the soils was determined volumetrically as reported by Beck (1971). For this purpose, 20 ml of 0.2 M phosphate buffer (pH 6.8) and 10 ml of 3% substrate solution were added to 5 g of soil sample. After waiting for 30 minutes, the amount of O_2 released at laboratory temperature (20 ^oC) after 3 minutes of the substrate solution mixed with the soil in the Scheibler calcimeter was determined volumetrically. Each analysis was performed in 3 replications and the findings were expressed as µl O_2 g^{-1} dry soil.

Statistical Analyses

SPSS 17.0 package program was used to determine the relationships between catalase enzyme activity and different profiles, land cover and elevation in soil samples of the study area.

Results and Discussion

Four profiles were opened on the Southwest-Northeast section and soil samples were taken from each profile based on horizon. Some physical-chemical analysis results of the soils in the study area are given in Table 1.

Table 1. Classification of Soils in the Study Area, Physiography, Land Use, Elevation and Some Physical-Chemical Analysis Results

Horizon	Depth (cm)	pH	EC ($dS.m^{-1}$)	$CaCO_3$ (%)	O.M (%)	Exchangeable Cations ($cmol.kg^{-1}$)			CEC ($cmol.kg^{-1}$)	Texture (%)			
						Na^+	K^+	$Ca^{++}+Mg^{++}$		Clay	Silt	Sand	Class
CD-P4 / Typic Haplustert / Foot slope/ Dry farming / 25 m													
Ap	0-23	7.50	0.17	0.20	1.65	0.22	1.67	40.91	42.8	56.2	23.1	20.7	C
Bss1	23-65	7.30	0.44	0.98	1.26	0.25	1.47	39.64	41.4	62.6	12.8	24.5	C
Bss2	65-106	8.25	0.17	1.10	1.09	1.33	1.41	37.59	40.3	68.4	15.8	15.8	C
C	106+	8.14	0.11	2.67	0.14	1.35	1.40	36.04	39.9	78.4	2.8	18.8	C
AB-P4 / Lithic Ustorthent / Back slope / Degraded forest / 42 m													
Ap	0-24	7.87	0.55	0.49	2.35	0.41	0.28	42.24	42.9	32.1	27.9	40.1	CL
Cr	24+	8.04	0.10	0.29	0.55	1.03	0.15	14.20	15.4	17.2	17.1	65.7	SL
CD-P3 / Typic Haplustert / Lowland / Pasture / 132 m													
A	0-12	7.05	0.16	0.79	1.71	0.35	0.24	40.17	40.8	41.5	24.2	34.3	C
Bss1	12-48	7.72	0.19	0.29	1.69	0.74	0.31	48.07	49.1	68.5	18.3	13.2	C
Bss2	48-89	7.79	0.34	1.37	0.59	1.31	0.41	47.25	48.9	49.8	26.4	23.9	C
C	89+	7.96	0.30	1.18	0.17	1.26	0.24	32.84	34.4	40.3	34.2	25.5	C
CD-P2 / Lithic Ustorthent / Shoulder / Pasture /185 m													
A	0-16	7.03	0.19	0.50	2.25	0.28	1.02	33.16	34.5	34.4	25.5	40.1	CL
Cr	16+	6.93	0.25	0.20	0.42	0.45	1.24	9.39	11.1	17.1	8.4	74.5	SL

pH: Soil reaction, EC: Electrical Conductivity, OM: Organic matter, C: Clay, Si:Silt, S:Sand

The profile coded as CD-P4 is the deep soil formed on the base land. The entire profile has a clay texture, with the clay content varying between % 56.2 and % 78.2. Although the cation exchange capacities (CEC) are 42.8 $cmol.kg^{-1}$ on the surface due to the amount of organic matter and clay content, this amount decreases towards the depths. This situation is also valid for the amount of organic matter, which is % 1.65 on the surface but decreases to % 0.14 after 65 cm. The soil reaction is slightly alkaline and pH values vary between

7.05 and 8.25. Calcium carbonate ($CaCO_3$) is present in very small amounts in the profile, measuring % 0.20 at the surface and increasing slightly to % 2.67 in the deeper layers. In addition, salinity and alkalinity problems are not observed in this profile.

The profile coded as AB-P4 is shallow soils with slightly steep slopes (% 6-12) on back slope lands. While the surface soil has a clay loam texture, the texture turns into sandy loam in the intensely altered parent material underneath. Although the CEC is 42.9 cmol.kg^{-1} on the surface due to the amount of organic matter and clay content, it decreases to 15.4 cmol.kg^{-1} after 24 cm. Although the amount of organic matter is % 2.35 on the surface, it decreases to % 0.55 in the subsurface layer. The soil reaction is slightly alkaline and pH values vary between 7.87 to 8.04. $CaCO_3$ is present in very small amounts in the profile. In addition, salinity and alkalinity problems are not observed in this profile.

The profile coded as CD-P3 is situated on a gently sloping land located between the lower and upper slope areas. The soils in these lands, which generally have pasture cover, are deep and heavy in texture. The clay content in the profile varies between %40.3 and %68.5. Although the CEC is 42.80 cmol.kg^{-1} at the surface, this amount decreases towards depth. Although the amount of organic matter is % 1.71 on the surface, it decreases to % 0.59 after 48 cm. The soil reaction is slightly alkaline and pH values vary between 7.05 and 7.96. $CaCO_3$ is present in very small amounts in the profile, measuring % 0.29 at the surface and slightly increasing to % 1.37 in the deeper layers. In addition, salinity and alkalinity problems are not observed in this profile.

The profile coded as CD-P2 is the highest profile at 185 m above sea level on the Southwest-Northeast section and its physiographic landform is slope lands. While the surface soil has a clay loam texture, the texture turns into sandy loam in the intensely altered parent material underneath. Although CEC is 34.46 cmol.kg^{-1} at the surface, it decreases to 11.09 cmol.kg^{-1} after 16 cm. Although the amount of organic matter is % 2.25on the surface, it decreases to % 0.42 in the subsurface layer. The soil reaction is slightly alkaline and pH values vary between 6.93 and 7.03. $CaCO_3$ is present in very small amounts in the profile. In addition, salinity and alkalinity problems are not observed in this profile.

Catalase Enzyme Activity of Soils

Surface and subsurface soil samples were taken to determine the catalase enzyme activity of the soils. For this purpose, catalase enzyme activity was carried out in 3 replications and the results of this analysis are given in Table 2. According to the analysis results, it was determined that the catalase enzyme activity of the soil samples taken from the opened profiles varied between 14.175-325.800 µl O_2 g^{-1} dry soil. The catalase enzyme activity was determined to be higher in the upper soil layers compared to the lower layers.

Table 2. The Catalase Enzyme Activity Results of Soil Samples Taken from Profiles Opened in the Study Area

Horizon	Depth (cm)	Catalase Enzyme Activity (µl O_2 g^{-1})
CD-P4 / Foot slope		
Ap	0-23	325.800
Bss1	23-65	295.904
AB-P4 / Back slope		
Ap	0-24	105.191
Cr	24+	14.175
CD-P3/ Lowland		
A	0-12	151.759
Bss1	12-48	119.189
CD-P2 / Shoulder		
A	0-16	257.785

Relationships Between Catalase Enzyme Activity and Profile, Land Cover and Elevation

The results of the biological analysis were statistically evaluated in 3 different ways: between soil profiles, land cover and elevation. Statistical results regarding changes in catalase enzyme activities of soils located on the Southwest-Northeast section are given in Table 3. When the statistical relationship between catalase enzyme activity and different profiles, land cover and elevation was examined, it was determined that the effect of different profiles and different elevations on catalase enzyme activity in the soil was significant at the % 1 level ($P=0.000<0.01$), while the effect of different land cover types on catalase enzyme activity in the soil was insignificant ($P=0.886>0.05$).

Table 3. Changes in catalase enzyme activity with different profiles, land cover and elevation in soils in the study area

Profiles	Mean + Standard Error
CD-P4/ Foot slope	310.85±8.694a
AB-P4/Back slope	59.68±27.177c
CD-P2/Shoulder	257.78±9.045a
CD-P3/ Lowland	135.47±9.446b
Significant (P)	0.000
Land Cover	Mean + Standard Error
Dry farming	185.26±49.270
Pasture	176.24±26.571
Significant (P)	0.886
Elevation (m)	Mean + Standard Error
25	310.85±8.694a
42	59.68±27.177c
132	135.47±9.446b
185	257.78±9.045a
Significant (P)	0.000

Discussion

The profiles coded as AB-P4 and CD-P2 are located on sloped lands and these are shallow soils that do not have sufficient pedogenetic processes. These soils generally do not have any diagnostic horizons other than an ochric epipedon on the surface and a lithic contact within 50 cm depth below the surface. The soils are classified as Orthent suborder due to their location on slope land and as Ustorthent and Lithic Ustorthent suborder due to their moisture regime. The profiles coded as CD-P4 and CD-P3 were placed in the Vertisol order because of the high amount of swelling clays (50% or more along the profile), the cracks extending from the surface to deep during dry seasons, and the appearance of slip surfaces in places within the profile. Due to the ustic moisture regime, it is placed in the Ustert suborder and in the Typic Haplustert subgroup because it carries all the characteristics of the Haplustert large group.

The catalase enzyme activity was determined to be higher in the upper soil layers compared to the lower layers. This indicates that microbial biomass and metabolic activity are more concentrated in the upper soil layers. The intensification of microorganism activities, especially in surface horizons, is due to the fact that the organic matter accumulated in these layers serves as the main carbon and energy source for microbial metabolism. In this context, the diversity, density and composition of microbial communities in the soil vary depending on the soil depth. The uppermost layer of the soil, known as the A horizon, is formed by the decomposition of organic residues of plant origin and is the layer where biological activity such as microorganisms and earthworms is most intense. Therefore, surface soil horizons are much richer in organic matter compared to the lower layers (Brady and Weil, 2016; Lal, 2004). A significant decrease in catalase enzyme activity is observed toward the lower soil horizons. This is attributed to the fact that catalase activity is generally considered a bioindicator associated with the presence of aerobic microorganisms. Therefore, it was detected at higher levels in the upper soil layers where oxygen is more abundant.

The results of the biological analysis were statistically evaluated in 3 different ways: between soil profiles, land cover and elevation. According to the ANOVA test results, the effect of different profiles on catalase enzyme activity from the biological properties of the soil was found to be significant at the % 1 level ($P=0.000<0.01$). According to the DUNCAN method, the highest catalase enzyme activity was determined in the profiles coded as CD-P4 and CD-P2, respectively, while the lowest catalase enzyme activity was determined in profile AB-P4. This may be related to the clay content in the profiles. It is thought that there is a strong interaction between the amount and mineralogical structure of clay in the soil and microbial activity. Therefore, clay content is considered as an important factor that indirectly increases soil biological productivity and microbial enzyme activities. The effect of different land cover types on catalase enzyme activity was found to be insignificant ($P=0.886>0.05$). Therefore, there is no statistically significant difference between different land cover types and catalase enzyme activity in the soil. The effect of different elevations on catalase enzyme activity in soil was found to be significant at the % 1 level ($P=0.000<0.01$). According to the DUNCAN method, the highest catalase enzyme activity was observed at an elevation of 25 meters, while the lowest activity was recorded at 42 meters. It was determined that catalase enzyme activity initially decreases with increasing elevation, and then increases at higher elevations. The initial decrease in catalase enzyme activity is related to temperature, humidity and microbial pressure decrease. The subsequent increase may occur due to the activation of microorganisms specific to high altitudes, increased organic matter amount and new environmental balances.

In this study carried out in the Engiz basin located in the south of Bafra district within the borders of Samsun province, as a result of the enzyme analysis of soil samples taken from the section in the southwest-northeast direction, it was determined that the catalase enzyme activity was higher in the upper horizons compared to the lower horizons. It was observed that catalase enzyme activity, which is an important indicator for determining the presence of aerobic microorganisms, decreased with increasing soil depth within the profile. The main reason for this decrease is that the organic matter content, one of the main parameters affecting catalase activity, is found at lower levels in the lower horizons. In this context, it is predicted that organic matter supplementation applied to the soil will not only improve the physico-chemical properties of the soil but also increase catalase enzyme levels by increasing microbial activity.

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Determination Of The Relationships Between Soil Phosphorus Forms And Related Enzymes And Their Spatial Variations: A Case Study İn Bartın Hazelnut Fields

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Abstract

Understanding the spatial characteristics of soil properties will facilitate the identification of their relationships and the development of region-specific management techniques. The aim of this study was to obtain basic information on the variability of soil P form concentrations and phosphatase activities in hazelnut growing areas and to investigate the relationship between phosphorus forms, related enzymes, and some physicochemical properties. Soil samples were collected from hazelnut cultivation areas at depths of 0-30 cm. Phosphorus forms (eP, Ca_P, Fe_P, Al_P, Solb_P, ReducSol_P), alkaline phosphatase, and acid phosphatase enzyme analyses were used to determine some physicochemical properties of the soil. The data were evaluated using classical statistical and geostatistical methods. The study determined the general order of change of inorganic phosphorus fractions as Ca_P>Fe_P>Al_P>ReducSol_P>Solb_P. Statistically significant relationships were identified between available P availability in soils and some soil properties and phosphorus fractions.

Keywords: Soil phosphorus forms, soil phosphatase activity, geostatistics.

Introduction

Phosphorus (P) is an important element that affects various processes of plant growth, and its deficiency limits crop production in various regions of the world (Ayaga et al. 2006; Redel et al. 2011; Sharpley et al. 2018). Despite continuous phosphorus applications in agricultural production areas, soil phosphorus levels remain at critical levels for plant development (Smith, 2001; Zhu et al. 2003). It is reported that approximately 5.7 billion hectares of land worldwide have low phosphorus levels, which are insufficient to sustain plant production (Granada et al. 2018). Phosphorus is present in soils in two forms: organic and inorganic. Most of the phosphorus in soil is in inorganic form, such as iron, aluminium, calcium, etc., and the amount of these inorganic phosphorus forms is affected by various soil properties such as pH, $CaCO_3$, organic matter, clay, silt, and sand (Singh and Pathak, 1973). The varying solubility of inorganic phosphorus forms under different soil conditions allows these forms to provide information about the availability of phosphorus in soils under specific soil conditions (Yang and Jacobsen, 1990; Chand et al. 1991). Changing soil conditions, fertilisation programmes, and plant cover affect phosphorus transfers within and between these fractions (Uygur et al. 2017). Generally, the conversion of phosphorus applied to calcareous soils into Ca-bound P fractions limits phosphorus availability, preventing plants from utilising phosphorus adequately. More efficient utilisation of phosphorus by plants is possible by increasing the conversion of phosphorus applied to the soil into labile P

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fractions, which are held in the soil with low energy and have a useful structure. Considering that phosphorus transforms into fractions in the soil, implementing appropriate, conscious practices is of great importance in agriculture, both for plant development and for the proper use and sustainability of phosphorus, which has a short lifespan.

Phosphatase enzyme activity is the enzyme responsible for converting organic phosphorus, which is in a form that plants cannot utilise, into inorganic phosphorus, which is in a form that plants can utilise. Phosphatases are produced by plant roots, mycorrhizal and saprotrophic fungi, or bacteria, and exhibit different pH and temperature optima. Their production and activity play an important role in the soil phosphorus cycle (Caldwell 2005; Margalef et al. 2021; Nannipieri et al. 2011).

Mahdi (2018) examined the availability of phosphorus and changes in phosphorus fractions in the soils of Atabey Plain. In their study, they determined the physical and chemical properties of 71 surface soil samples (0–20 cm) and phosphorus fractions (labile P fraction), iron-bound P (CBD-P), Ca-bound P fraction (Ca-P) and residual or remaining P (Res-P) were determined. The study concluded that the average distribution of fractions in plain soils was Ca-P > Res-P > CBD-P > NaOH-Pt > NaOH-Pi > $NaHCO_3$-Pt > $NaHCO_3$-Pi > NaOH-Po > $NaHCO_3$-Po, and that land use was effective in the distribution of these fractions. In Karakaş (2018)'s study, which examined the P fractions (labile-P, Fe-bound-P, Ca-bound-P) and physical and chemical properties of cultivated and uncultivated soils in Mardin at a soil depth of 0-20 cm, it was reported that as pH increased, the amount of available P decreased in both areas, a decrease in the amounts of Fe-bound P and Ca-bound P. Additionally, the study noted that as clay and lime content increased, the amount of available P decreased, the amounts of Fe-bound P and Ca-bound P fractions increased, and there was no significant change in labile-P content. As the organic matter content increases, there is an increase in the ratios of labile-P and available P, while there is a decrease in the content of Fe-bound P and Ca-bound P fractions.

It is known that soil microbial properties exhibit high spatial-temporal variability (Cavigelli et al. 2005). Understanding the spatial variability of soil properties is important for determining soil constraints on plant nutrition and the appropriate management of soil resources (Couto et al. 1997). According to Peigné et al. (2009), the high spatial heterogeneity of soil properties, particularly microbial properties, can mask the effects of different soil management practices. Therefore, it is important to identify, predict, and map the spatial patterns of soil properties. Geostatistics is used to analyse the spatial patterns of soil physical and chemical properties (Katsalirou et al. 2010; Roger et al. 2014; Zhang et al. 2014), soil biogeochemical properties (Aşkin and Kizilkaya, 2006; Piotrowska and Długosz, 2012), and soil microbial variables and processes (Peigné et al. 2009; Katsalirou et al. 2010) in soil science. Semi-variogram models provide the information necessary for kriging, a method used to interpolate data at unmeasured points (Sebai et al. 2007). The objectives of this study are to obtain basic information about the variability of soil P forms concentration and phosphatase activities in areas where hazelnuts are grown, to evaluate the contribution of random variation to total soil variability, and to investigate the relationship between phosphorus forms and related enzymes and some physico-chemical properties.

Material and Methods

General Characteristics of The Study Area

It covers an area of approximately 2.272 km^2 and is located between 410.000–490.000 east and 4.570,000–4.630,000 north coordinates (WGS-84, Zone 36, Universal Transverse Mercator-UTM-m) (Figure 1).

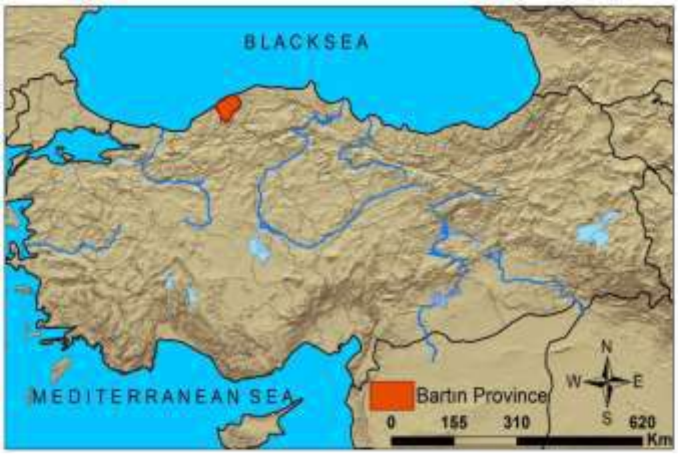

Figure 1. Work area location map

Most of the land in the north, northeast and south of the province is mountainous, rugged and steeply sloped (>45%), with elevations ranging from 0 m to 1.645 m above sea level. On the other hand, some parts of the west and southwest of Bartın province consist of gently sloping flat land (Figure 2).

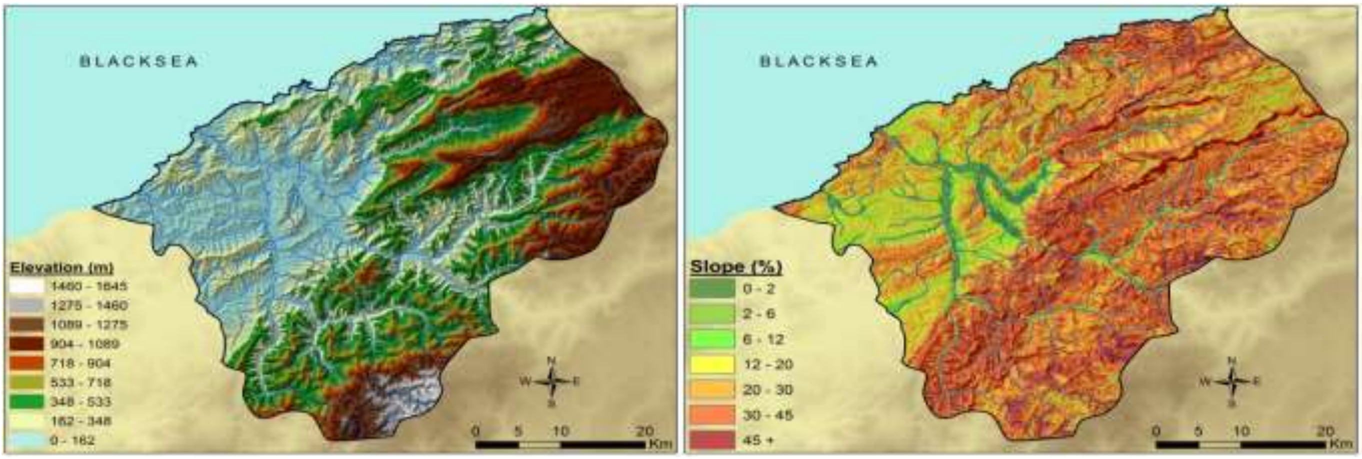

Figure 2. Elevation and slope maps of the study area

Bartın Province has a rainy climate and is quite rich in surface water resources. According to long-term meteorological data (1965–2021) for Bartın Province, the annual average temperature is 12.8 °C, and the annual average precipitation is 1042 mm. According to the Newhall simulation model (Van Wambeke, 2000), the soil moisture and temperature regimes in Bartın Province have been determined as udic (subgroup dry temptudic) and mesic. Bartın Province belongs to the Mesozoic era in terms of geology. Most of the sedimentary materials in the southwestern part of the area were brought by rivers during the Quaternary period. Sandstone, mudstone, and clayey limestone are common geological materials in the area, and volcanic and limestone rocks are found in the northern and northeastern parts of the study area. They are also found in alluvial sediment deposits brought by rivers during floods. According to the FAO-WRB (2014) soil classification, alisol-akrisol soils are widespread in the region, followed by chromic leptosol and oitic arenosol soils, and oitic fluvisol soils are also distributed in alluvial areas (Figure 3).

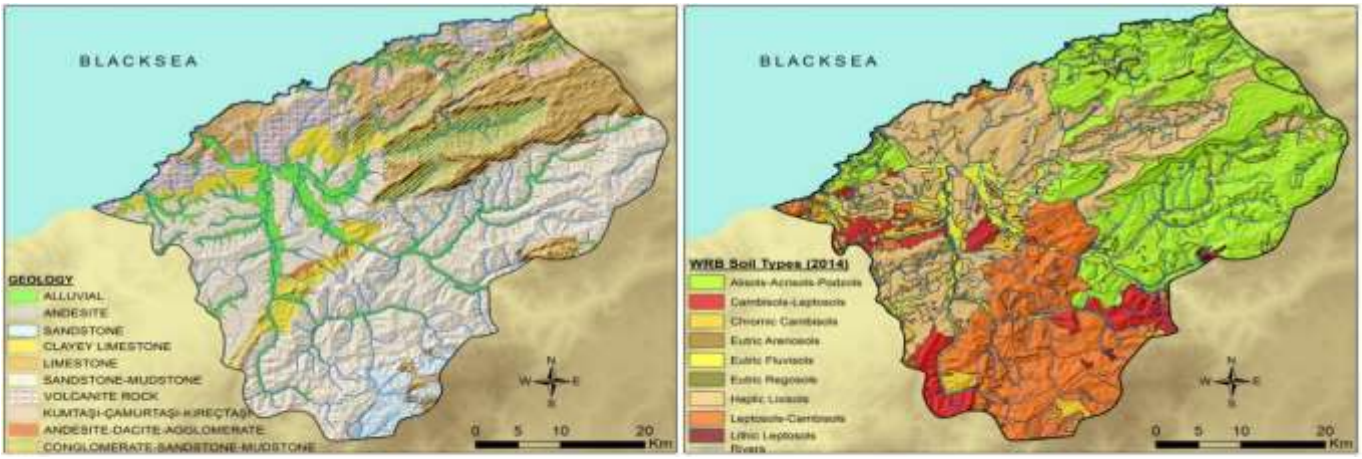

Figure 3. Geology and soil type maps of the study area

Soil samples and laboratory analyses

Soil samples were collected from the study area after the 2018 harvest in order to accurately represent the hazelnut cultivation areas. Soil samples were collected from 38 points within the hazelnut cultivation area at a depth of 0-30 cm using GPS coordinates (Figure 4).

The soil samples obtained were separated from coarse particles such as gravel and plant debris and dried under laboratory conditions. The dried soil samples were crushed with wooden mallets, passed through a 2 mm sieve, placed in polyethylene boxes and prepared for analysis. Phosphorus fractions were determined in the soil samples. Some physical, chemical, and enzymatic activities of the soils were also determined. The methods for these analyses are outlined in Table 1. Soil phosphorus fraction analyses were determined according to Kovar and Pierzynski (2009).

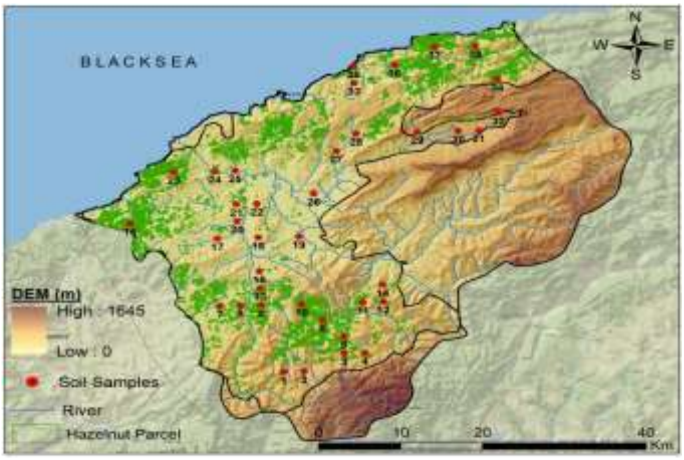

Figure 4. Map of soil samples in hazelnut plots

Table 1. Analysis methods for the parameters selected in the study

Parameters	Unit	Protocol	Reference
Texture (clay, silt and sand)	%	Hydrometer method	Bouyoucos (1951)
Organic mater (OM)	%	Wet oxidation method (Walkley-Black) with potassium dichromate ($K_2Cr_2O_7$)	Nelson and Sommers (1982)
pH		(w:v) soil-water suspension (1:1)	Soil Survey Staff (1992)
Electrical Conductivity (EC)	dS m^{-1}	(w:v) soil-water suspension (1:1)	Soil Survey Staff (1992)
$CaCO_3$	%	Scheibler calsimeter	Soil Survey Staff (1992)
$NaHCO_3$–P	mg kg^{-1}	The molybdophosphoric blue method	Olsen et al. (1954)
Acid phosphatase (ACPA) (EC3.1.3.2)	µg p-nitrophenol g^{-1} dry sample	0.25 ml toluene, 4 ml phosphate buffer (pH 6.5) and 1 ml of 0.115 Mp-nitrophenyl phosphate (disodium salt hexahydrate) solution were added to the 1 g sample and the samples were incubated for 1 h at 37 °C. The formation of p-nitrophenol was determined spectrophotometrically at 410 nm	Tabatabai and Bremner (1969)
Alkaline Phosphatase (ALPA) (EC3.1.3.1)	µg p-nitrophenol g^{-1} dry sample	0.25 ml toluene, 4 ml phosphate buffer (pH 11) and 1 ml of 0.115 Mp-nitrophenyl phosphate (disodium salt hexahydrate) solution were added to the 1 g sample and the samples were incubated for 1 h at 37 °C. The formation of p-nitrophenol was determined spectrophotometrically at 410 nm	Tabatabai and Bremner (1969)

Statistical and geostatistical analyses

Geostatistical methods were used to determine the spatial variability of soil phosphorus fractions and enzyme parameters. Geostatistical techniques are very useful for determining spatial distribution by estimating characteristics for unsampled locations, thereby reducing estimation errors and costs (Nielsen and Wendroth, 2003; Saito et al. 2005). There are many interpolation methods available for estimating the spatial distribution of parameters. One of the most commonly used multivariate interpolation methods is Inverse Distance Weighting (IDW). The inverse distance neighbourhood similarity method estimates values at unsampled points by using the linear combination of values at sampled points, leveraging inverse distance functions based on distances. Inverse distance neighbourhood interpolation is used in geographic information systems to create raster layers from point data. When the data is in a regular grid system, contour lines can be drawn through the interpolated values, and the map can be created as a vector contour map or a raster shaded map (Burrough and Mcdonnell, 1998). The estimates are determined using the following formula (Equation 1).

$$Z = [\sum_{i=1}^{n}(Zi/di^{m}) \ / \sum_{i=1}^{n}(1/di^{m})] \qquad (1)$$

Z: estimated value, Zi: value at the known point, di: distance between point i and the point whose value is to be estimated, m: weighting factor (usually used between 1 and 5). In this study, the weight forces commonly used in IDW estimation (1st, 2nd, and 3rd order) were employed (Pirmoradian et al. 2010; Keshavarzı and Sarmadian, 2012).

Some descriptive statistics and correlation analyses were performed using SPSS 20.0v. to determine the productivity relationships of certain physico-chemical properties of soils and the content of useful nutrient elements.

Results and Discussion

Descriptive statistics of the study area

Descriptive statistics for some of the physical and chemical properties of the study area soils and different phosphorus fractions are given in Table 2. The average clay content in the study area was determined to be 40.86%. Soil pH values ranged from 5.77 to 7.89, with an average lime content of 2.70%, organic matter (OM) of 2.73%, and electrical conductivity (EC) of 0.47 dSm-1. The highest coefficient of variation in the physico-chemical properties of the study area soils was determined in the lime content, while the highest coefficient of variation among the phosphorus fractions was determined in the Al_P fraction. Positive skewness was observed in the Al_P, Fe_P, Solb_P, and ReducSol_P phosphorus fractions. This positive skewness in these fractions indicates that, in general, excessive increases have occurred in some soils due to extensive fertilisation practices or the effects of soil formation processes. In general, the available P content is low in soils formed on calcareous parent material in arid and semi-arid regions. In the study area soils, Olsen-P ($NaHCO_3$-Pi), which is considered available P, ranges from 1.25 to 116.42 mg kg^{-1}, with an average of 12.81 mg kg^{-1}. This indicates that the soils in areas where hazelnuts are grown are under quite high chemical fertilisation. When excessive fertilisation is applied to calcareous soils, Ca_P accumulates, likely due to the abundance of Fe/Al oxides or carbonate minerals and the management of thermodynamic conditions. This is an expected situation, considering that Ca_P compounds are more stable under alkaline calcareous conditions and Fe solubility is low (Lindsay, 1979; Uygur and Karabatak, 2009).

In this study, the general order of change in inorganic phosphorus fractions is Ca_P>Fe_P>Al_P>ReducSol_P>Solb_P. The inorganic phosphorus fractions were found to range from 22.42 mg kg^{-1} to 1449 mg kg^{-1}, with an average of 474.20 mg kg^{-1}. In the study, it was found that Ca_P, one of the inorganic phosphorus fractions, was the dominant inorganic phosphorus fraction in all soils in the study areas where hazelnut cultivation was practised. Çimrin (2020) determined that the amounts of inorganic phosphorus fractions ranged from 163.17 mg kg^{-1} to 951.12 mg kg^{-1}, with an average of 722.08 mg kg^{-1}. Many researchers have reported that the degree of decomposition and fragmentation is relatively low, rainfall is insufficient to leach alkaline cations from the soil profile, and the inorganic phosphorus fraction Ca_P is the most abundant in calcareous and alkaline soils (Shen and Jiang, 1992; Azadi et al. 2015). The conversion of phosphorus applied to calcareous soils into Ca-bound P fractions limits phosphorus availability and prevents plants from utilising phosphorus sufficiently. However, increasing the conversion of phosphorus applied to the soil into labile-P fractions with a useful structure allows plants to utilise phosphorus more effectively (Lombi vd. 2005).

Table 2. Descriptive statistics of the study area

Parameter	Min	Max	Mean	SD	CV,%	Variance	Skewness	Kurtosis
Sand, %	7.09	65.94	31.05	14.71	47.39	216.50	0.750	-0.193
Silt, %	3.74	49.81	28.09	8.86	31.52	78.42	-0.213	1.413
Clay,%	18.10	66.79	40.86	12.65	30.96	159.96	-0.017	-0.715
pH (1:1)	5.77	7.89	7.15	0.64	8.90	0.41	-0.861	-0.570
EC (1:1)	0.11	1.22	0.47	0.26	55.49	0.07	0.903	0.569
$CaCO_3$ %	0.01	16.67	2.70	3.84	142.07	14.76	1.917	3.806
OM, %	0.55	5.07	2.73	1.23	44.84	1.50	0.094	-0.800
eP, mg kg^{-1}	1.25	116.42	12.81	25.61	199.85	655.65	3.752	13.806
ALPA, µg p-nitrophenol g^{-1}	154.66	496.82	352.90	90.49	25.64	8188.88	-0.525	-0.701
ACPA, µg p-nitrophenol g^{-1}	58.11	381.99	186.04	82.04	44.10	6731.02	0.683	0.066
Al_P, mg kg^{-1}	11.97	1229.86	60.70	195.70	322.39	38299.73	6.076	37.235
Fe_P, mg kg^{-1}	19.94	296.5	72.85	55.98	76.85	3133.85	2.361	6.464
Ca_P, mg kg^{-1}	22.42	1449.43	474.20	384.48	81.08	147824.70	0.689	0.146
$P_{soluble}$, mg kg^{-1}	4.52	144.13	10.76	22.56	209.70	508.74	5.904	35.622
$P_{reductant}$, mg kg^{-1}	4.75	231.59	59.86	43.24	72.23	1869.55	2.831	9.160

ALPA: Alkali fosfataz enzimi, ACPA: Asit fosfataz enzimi

Spatial variability of phosphorus properties

The spatial distribution of alkaline phosphatase enzyme (ALPA) and acid phosphatase enzyme (ACPA) activities in 38 soil samples taken from hazelnut plots in Bartın Province is shown in Figure 5. Alkaline phosphatase enzyme and acid phosphatase enzyme activities were found to be high in hazelnut plots distributed in the central and southwestern parts of the study area, while they were found to be lower in hazelnut plots located in the northern and northwestern parts.

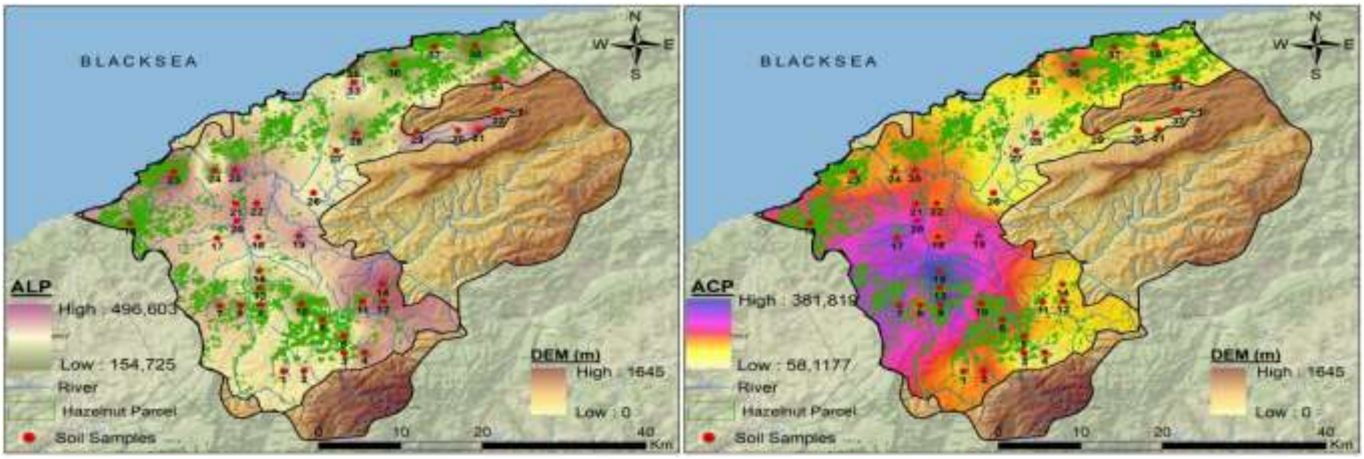

Figure 5. Maps showing the spatial distribution of alkaline phosphatase enzyme (ALPA) and acid phosphatase enzyme (ACPA) activities.

Distribution maps of extractable phosphorus (eP) and phosphorus interactions with calcium (Ca_P), iron (Fe_P) and aluminium (Al_P) are shown in Figure 6. Extractable phosphorus was determined to range from a minimum of 1.25 ppm to 116.08 ppm in the study area, generally showing a moderate to low trend. Ca_P generally exhibits an increasing trend in the central parts of the study area, but the southern parts are around 22 ppm. Additionally, the most significant elements affecting phosphorus availability in acidic soils are Al and Fe. When examining the distribution of phosphorus with these elements, Al_P shows an increase in the central parts of the study area, while Fe_P shows an increase in the northern parts of the area.

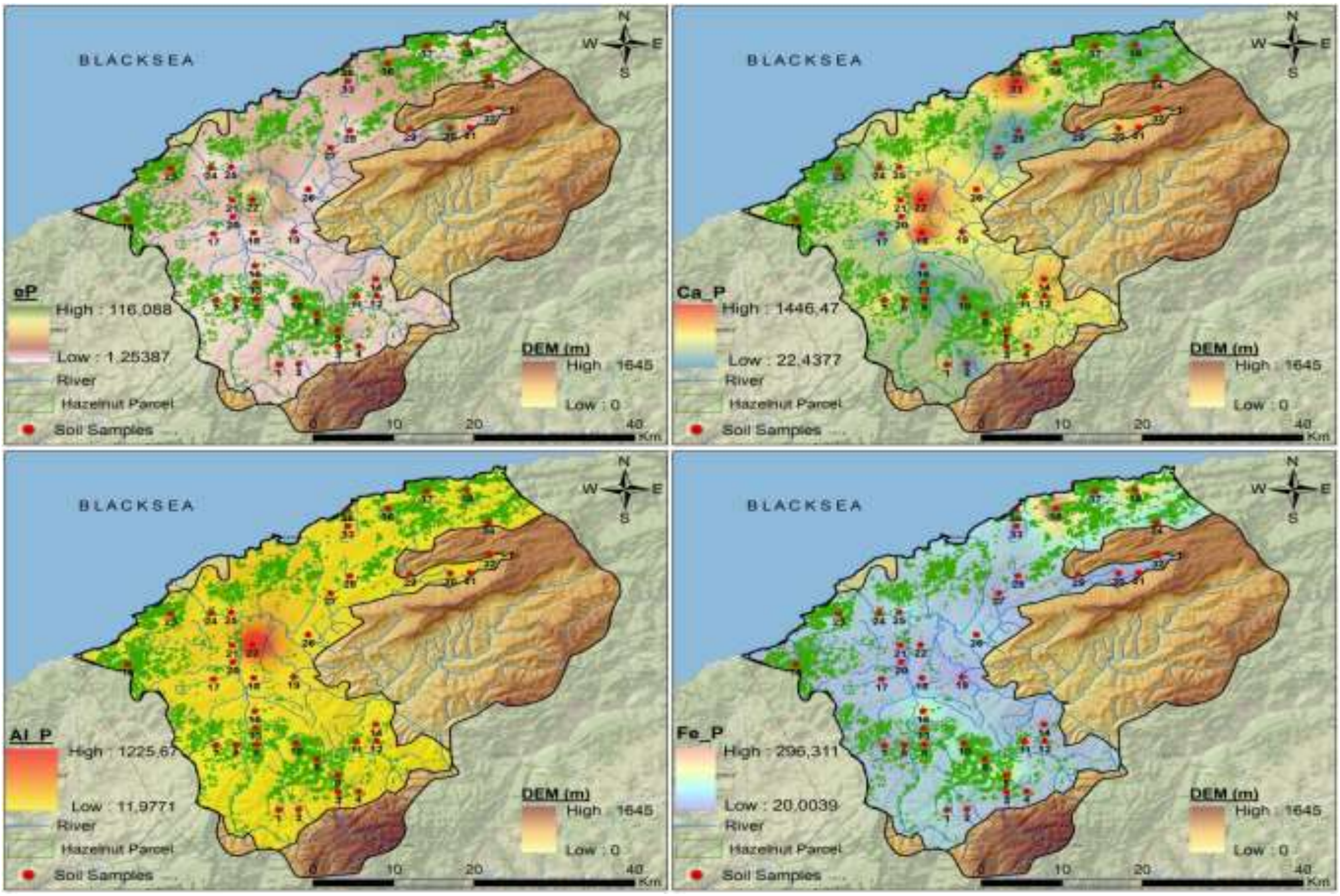

Figure 6. eP, Ca_P, Fe_P and Al_P distribution maps

The distributions of soluble and weakly bound phosphorus (Solb_P) and reduced soluble phosphorus (ReducSol_P) are shown in Figure 7. Soluble and weakly bound phosphorus varies between 4.521 ppm and 143.648 ppm in the study area, generally showing a moderate to low distribution trend, while similar distribution patterns are observed for reduced-soluble phosphorus.

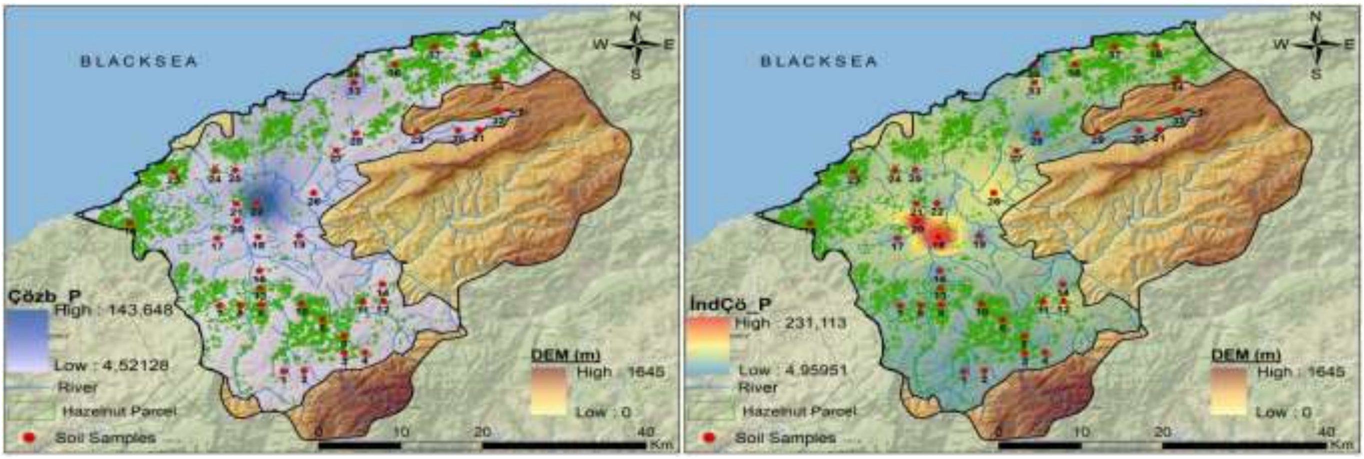

Figure 7. Maps of soluble and weakly bound phosphorus (Solb_P) and reduced soluble phosphorus (ReducSol_P) phosphorus distributions

Correlation between the characteristics examined

The Pearson correlation coefficients between certain soil physico-chemical properties and P fractions are given in Table 3. There is a positive correlation between the Ca_P fraction and pH (r=0.378*), $CaCO_3$ (r=0.591*), and eP (r=0.411*). Significant negative correlations were observed between the Fe_P fraction and pH (r=-0.453**) and ACPA (r=-0.569**). Significant positive correlations were determined between available P and soluble P (r=0.688**) and Al_P (r=0.680**). Positive correlations were observed between soluble P and Al_P (r=0.991**). Additionally, significant positive relationships were identified between Olsen-P phosphorus, which represents plant-available phosphorus in the soil, and inorganic phosphorus fractions, including Al_P, Ca_P, and soluble P. In Çimrin's (2020) study, negative significant relationships were found between Olsen-P and soil pH, lime, and sand content, while positive significant relationships were found between salinity and organic matter content. Ahmad et al. (2019) identified positive relationships between soil Olsen-P and organic matter content.

Table 3. Correlations between the characteristics examined

	Sand	Silt	Clay	pH	EC	$CaCO_3$	OM	eP	ALPA	ACPA	$P_{çözünür}$	Al_P	Fe_P	$P_{reductant}$	Ca_P
Sand	1.00														
Silt	-0.51**	1.00													
Clay	-0.80**	-0.09	1.00												
pH	-0.203	-0.045	0.268	1.00											
EC	-0.382*	-0.088	0.50**	0.214	1.00										
$CaCO_3$	-0.364*	0.035	0.39*	0.47**	0.231	1.00									
OM	-0.56**	0.364*	0.405*	-0.065	0.119	0.123	1.00								
eP	-0.012	0.147	-0.089	0.051	0.053	0.072	0.121	1.00							
ALPA	-0.53**	0.44**	0.310	0.44**	0.218	0.36*	0.46**	0.066	1.00						
ACPA	-0.363*	0.095	0.356*	-0.56**	0.119	-0.179	0.48**	-0.13	-0.112	1.00					
$P_{soluble}$	-0.118	0.011	0.129	0.093	-0.142	0.269	0.298	0.68**	0.134	-0.04	1.00				
Al_P	-0.129	0.042	0.120	0.066	-0.155	0.207	0.307	0.68**	0.127	-0.021	0.99**	1.00			
Fe_P	0.300	0.056	-0.38*	-0.45**	-0.34*	-0.36*	-0.158	0.018	-0.58**	0.158	-0.080	-0.06	1.00		
$P_{reductant}$	-0.172	-0.03	0.227	0.103	0.066	0.039	0.000	-0.119	0.107	0.011	-0.091	-0.09	-0.07	1.00	
Ca_P	-0.266	0.07	0.261	0.378*	0.290	0.591*	0.124	0.411*	0.376*	-0.259	0.485	0.441	-0.17	0.28	1

ALPA: Alkaline phosphatase enzyme, ACPA: Acid phosphatase enzyme, ReducSol_P: Reduced soluble P, Solb_P: Soluble P *. Correlation is significant at the 0.05 leve, **. Correlation is significant at the 0.01 level.

Conclusion

P fractions are key to making decisions regarding sustainable P management in specific regions based on phosphatase enzyme activity. In this study, a total of 38 surface soil samples were collected from hazelnut fields in Bartın Province. The average distribution order of the fractions in these areas was determined as Ca_P>Fe_P>Al_P>ReducSol_P>Solb_P. According to the study, the conversion of phosphorus applied to calcareous soils into Ca-bound P fractions limits phosphorus availability and prevents plants from adequately utilising phosphorus. Additionally, the study identified statistically significant relationships between soil available P content and certain soil properties and phosphorus fractions. The findings highlight the role of certain soil properties in regulating phosphorus dynamics and provide valuable insights for developing phosphorus management strategies in various agricultural systems.

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Effect of Elemental Sulfur Treatment on Available Micronutrient Elements (Fe, Zn and Mn) in Calcareous and Alkaline Soils

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Abstract

Plants need microelements for optimum development. In arid and semiarid soils, high lime, pH and oxide compounds limit the uptake of micronutrients such as iron (Fe), zinc (Zn) and manganese (Mn) by plants. The aim of this study is to determine the effect of raw phosphate material and elemental sulfur (S^0) treatment to a highly calcareous and alkaline soil on some available microelements (Fe, Zn and Mn). The study was carried out in pots according to the randomized plot design with 3 replications. Elemental S^0 was applied to pots containing one (1) kg of soil at the rate of 0, 80, 160 and 320 mg kg^{-1} and mixed homogeneously. Soil samples were taken from the pots brought to field capacity on the 45th, 90th and 135th days and with DTPA extractable Fe, Zn and Mn concentrations were determined. According to the obtained data, the increase in available Fe, Zn and Mn concentrations in the soils with the increase in elemental S^0 application doses was found to be statistically significant. As a result, it was determined that elemental S^0 application to high calcareous and alkaline soils increased the available Fe, Zn and Mn contents.

Keywords: Elemental sulfur, iron, manganese, raw phosphate, soil.

Introduction

High calcium levels (calcareous soils) and soil pH are the main causes of the fixation of certain elements such as phosphorus (P), iron (Fe), and zinc (Zn) in soils and, therefore, nutrient deficiencies (Hemmaty et al., 2012; Saltali et al., 2017). Most of the soil in Türkiye has a pH above 7 and high lime content (Güçdemir, 2006). A large portion of Türkiye's soils have a pH above 7 and high lime content (Güçdemir, 2006). One of the reasons why high pH is a factor limiting soil productivity is that it causes P and some microelements (Fe, Zn, and Mn) to become immobile in the soil (Durak et al., 2007;Yaraş and Daşgan, 2012). The availability of plant nutrients depends on the size and valence of the molecule.

In alkaline soils, elemental sulfur (S^0), sulfuric acid, ammonium sulphate, calcium sulphate treatments, or the addition of organic matter to the soil can be used to increase the concentration of H^+ ions in the environment and/or activate existing H^+ ions (Yaraş and Daşgan, 2012). The treatment of S^0 is one of the primary and most economical methods used to lower soil pH (Akay et al., 2019). Elemental sulfur mixed into the soil through various means is oxidized by soil bacteria and converted into sulfuric acid. This acid helps lower soil pH (Uçgun et al., 2019). Abdou (2006) and El-Tarabily et al. (2006) reported that the biochemical oxidation of elemental sulfur lowers soil pH and dissolves $CaCO_3$ in alkaline calcareous soils, thereby creating more suitable soil conditions for plant growth and improving the availability of plant nutrients.

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Hemmaty et al. (2012) conducted a study on apple trees in which they applied two different sulfur treatments (sulfur, sulfur+organic matter) at two rates (2 kg and 4 kg/tree) to lower soil pH and increase P, Fe, and Zn uptake. As a result, it was reported that sulfur applications lowered pH and thus increased Fe and Zn concentrations by 11–30% compared to the control. Calcareous soil has high $CaCO_3$ and alkaline pH, which greatly reduce the solubility of Fe, Zn, Mn, and Cu (Rahman et al., 2011).

In recent years, raw phosphate and S^0 have been applied together to meet plant P needs. Numerous studies have been conducted on the effects of S^0 application on micronutrient levels in alkaline soils. However, studies on the effects of S^0 on micronutrient levels when applied with raw phosphate are limited. The aim of this study was to determine the effect of applying different doses of S^0 together with raw phosphate to a soil with high limestone content and alkaline pH on some microelements (Fe, Zn and Mn).

Material and Methods

Soil samples were collected from a depth of 0–30 cm from the Research and Application Garden of Kahramanmaras Sutcu Imam University for use in the study. The soil used in the experiment (silt 11%, sand 71%, clay 18%) has a sandy loam texture. The soil pH is 7.80 and it is classified as non-saline. The lime content (18.84%) is high, while the organic matter content (2.01%) is moderate. The raw (rock) phosphate (25% P_2O_5) was imported from Egypt, with a pH of 2.43 and an EC of 18.10 dS m^{-1} The elemental sulfur (S^0) content is 98%.

Soil samples taken from the field were left to dry in the shade, and the dried soil was sieved through 2 mm sieves, weighed to 1 kg, and transferred to pots. The experiment was conducted in three replicates according to the experimental design. Ground raw phosphate was applied to the pots at rates of 20 kg da^{-1}, 40 kg da^{-1}, 80 kg da^{-1}, and 20 kg da^{-1}, 40 kg da^{-1}, 80 kg da^{-1} S^0 calculation, 80, 160, and 320 mg kg^{-1} of raw phosphate and S^0 were applied to 1 kg of soil and mixed homogeneously with the soil. Subsequently, 400 ml of water was applied to the pots to bring them to field capacity. Water was added to the pots as needed to maintain field capacity over time. Soil samples were taken homogeneously from the pots on days 45, 90, and 135 of the experiment and left to dry. The dried soil samples were placed in sealed bags and stored in a cool environment. Microelement analyses of the soils were extracted using the DTPA method developed by Lindsay and Norvell (1978) to determine the concentrations of Fe, Mn, and Zn in calcareous and near-neutral pH soils and read on an AAS device. Variance analysis (ANOVA) was performed to compare the data obtained in the study, and the Tukey Multiple Comparison Test was used to determine the differences between the means.

Results and Discussion

Effect of Elemental Sulfur Treatments on Available Iron Concentration

The effect of elemental sulfur (S^0) and raw phosphate treatments on the average available iron (Fe) concentration on days 45, 90, and 135 is shown in Table 1. No statistically significant effect of S^0 treatment on the available Fe content of soils was observed on day 45. On day 90, an increase in available Fe concentration in soils was observed with increasing S^0 doses. These increases were found to be statistically significant at the $p<0.01$ level in the 20 kg da^{-1} and 40 kg da^{-1} S^0 treatments. Although the 0 and 80 kg da^{-1} S^0 treatments were in the same group, the available Fe concentration was higher in the 80 kg da-1 S^0 treatment. This indicates that S^0 treatment increases the available Fe content. Karimi et al. (2019) reported that S^0 treatment causes soil acidification and, consequently, increases the available Fe concentration in soils. On the 135th day of the study, the average lowest available Fe content in the control group was 12.27 mg kg^{-1}, while the highest was 13.07 mg kg^{-1} in the 80 kg da^{-1} treatment. The increase in available Fe content with increasing S^0 treatment dose was found to be statistically significant ($p<0.05$). Maltaş et al. (2022) reported that S^0 treatment increased the available Fe content in alkaline and calcareous soils.

Effect of Elemental Sulfur Treatments on Available Zinc Concentration

The effect of elemental sulfur and raw phosphate treatments on the average available zinc (Zn) content on days 45, 90, and 135 is shown in Table 2. When examining the effect of elemental sulfur treatment on Zn at 45 days, the available Zn content of soils was 0.65 mg kg^{-1} at the S^0 control dose, while it increased to 0.67 mg kg^{-1} at an 80 kg da^{-1} S^0 treatment. In general, as the S^0 treatment dose increased, the available Zn concentration in soils also increased. This increase was found to be statistically significant at the $p<0.05$ level. On the 90th day of the experiment, the available Zn content increased with increasing S^0 treatment rate, and the difference between the rates was found to be statistically significant at the $p<0.05$ level after the 40 kg da^{-1} S^0 treatment.

Table 1. The average values of available Fe from elemental sulfur and raw phosphate treatment

45th day		Raw Phosphate Doses (kg da^{-1}) 0	20	40	80	Mean
S^0 Doses (kg da^{-1})	0	11.28de	12.77a-e	14.16abc	12.80a-e	12.75
	20	14.53a**	13.03a-e	11.52de	12.21c-e	12.82
	40	14.50ab	12.35b-e	12.11cde	11.41de	12.59
	80	11.71de	12.29cde	11.12e	13.41a-d	12.13
	Mean	13.00	12.61	12.22	12.46	
90th day		**Raw Phosphate Doses (kg da^{-1}) 0**	**20**	**40**	**80**	**Mean**
S^0 Doses (kg da^{-1})	0	12.23c-f	14.00b-e	13.12def	12.24f	13.15C
	20	14.35bcd	13.60b-f	14.85b	12.69ef	13.87B
	40	13.63b-f	17.81a**	14.94b	12.21f	14.65A**
	80	13.23c-f	13.93b-e	14.64bc	12.69ef	13.62BC
	Mean	13.61B	14.84A**	14.39A	12.46C	
135th day		**Raw Phosphate Doses (kg da^{-1}) 0**	**20**	**40**	**80**	**Mean**
S^0 Doses (kg da^{-1})	0	10.80ef	11.63def	13.36bcd	13.28bcd	12.27B
	20	11.36def	12.11c-ff	14.05bc	12.21b-f	12.43AB
	40	10.67f	12.88b-e	12.69b-f	14.4a**	12.66A
	80	11.65def	12.69b-f	12.35ab	14.4bc	13.07A**
	Mean	11.12C	12.33B	13.61A	13.97A**	

**:p<0.01 *:p<0.05

When the effect of S^0 on available Zn was examined on the 135th day of the study, there was a slight increase when the treatments rates of 0 kg da^{-1} and 80 kg da^{-1} were compared. However, this increase was not statistically significant. When the available Zn contents of soil samples taken at different times were evaluated as a whole, the available Zn content increased with S^0 treatment. This increase can be attributed to the acidic compounds formed by the oxidation of S^0. Wang et al. (2008) reported that sulfur treatment to soils increases the solubility of metals such as Zn in soils. Cui et al. (2004) reported that when 200 mmol S was treatment to the soil, the initial soil pH value was 7.7, but after 54 days, the soil pH value decreased by 0.30 units, and as a result, the $CaCl_2$-extractable Zn concentration increased significantly. Orman and Ok (2012) reported that soil pH decreased with sulfur treatment. In this study, soil pH decreased on day 135, and this decrease was found to be statistically significant at the p<0.01 level (Ekici et al., 2025).

Table 2. The average values of available Zn from elemental sulfur and raw phosphate treatments

45th day		Raw Phosphate Doses (kg da^{-1}) 0	20	40	80	Mean
S^0 Doses (kg da^{-1})	0	0.51c	0.61abc	0.64abc	0.65abc	0.60B
	20	0.63abc	0.62abc	0.65abc	0.71ab	0.65AB
	40	0.63abc	0.63abc	0.75a*	0.59bc	0.65AB
	80	0.68ab	0.64abc	0.71ab	0.64abc	0.67A*
	Mean	0.61B	0.62B	0.69A**	0.65AB	
90th day		**Raw Phosphate Doses (kg da^{-1}) 0**	**20**	**40**	**80**	**Mean**
S^0 Doses (kg da^{-1})	0	0.63c	0.73bc	0.71bc	0.69c	0.69B
	20	0.69bc	0.73bc	0.68bc	0.63c	0.68B
	40	0.65c	0.69bc	0.94a	0.67bc	0.73AB
	80	0.75bc	0.77bc	0.82ab	0.65c	0.74A*
	Mean	0.68AB	0.73AB	0.79A*	0.66C	
135th day		**Raw Phosphate Doses (kg da^{-1}) 0**	**20**	**40**	**80**	**Mean**
S^0 Doses (kg da^{-1})	0	0.67cd	0.67cd	0.67cd	0.74abc	0.69
	20	0.63cd	0.71bcd	0.70bcd	0.65cd	0.67
	40	0.59d	0.85a**	0.65cd	0.66cd	0.69
	80	0.71bcd	0.71bcd	0.81ab	0.64cd	0.72
	Mean	0.65C	0.74A*	0.71AB	0.67BC	

**:p<0.01 *:p<0.05

Effect of Elemental Sulfur Treatment on Available Manganese Concentration

The effect of elemental S^0 and raw phosphate treatments on available manganese (Mn) concentration on days 45, 90, and 135 is shown in Table 3. When examining the effect of S^0 treatment on available Mn on day 45, it was found that the increase in available Mn concentration was statistically significant (p<0.01) with increasing S^0 doses. The lowest average available Mn content was obtained in the control group at 4.31 mg kg^{-1}, while the highest available Mn content was obtained at 9.10 mg kg^{-1} with an S^0 application dose of 80 kg da^{-1}. On the 90th day of the study, when the effect of S^0 on the average available Mn was examined, the increase in available Mn concentration with increasing S^0 doses was found to be statistically significant (p<0.01). The highest average available Mn content was obtained at an average of 9.87 mg kg^{-1} at an S^0 dose of 80 kg da^{-1}. On the 135th day of the experiment, the average highest Mn concentration was 7.85 mg kg^{-1} at an S^0 treatment rate of 80 kg da^{-1} and 6.20 mg kg^{-1} at an S^0 dose of 0 kg da^{-1}. The average available Mn concentration also increased significantly (p<0.01) with increasing elemental sulfur treatment rates. El-Kholy et al. (2013) reported that sulfur treatment to soils increases the solubility of certain plant nutrient elements, including Mn, in soils, thereby increasing the uptake of metallic ions by plants. It has been reported that soil pH has the greatest effect on Fe and Mn among microelements (Uçgun et al., 2019).

Table 3. The average values of available Mn for elemental sulfur and raw phosphate treatments

		Raw Phosphate Doses (kg da^{-1})				
45th day		0	20	40	80	Mean
S^0 Doses (kg da^{-1})	0	4.78c	1.91d	5.12c	5.44c	4.31C
	20	7.95b	3.78cd	7.39b	7.89b	6.76B
	40	7.55b	10.04a	8.79ab	7.57b	8.49A
	80	7.80b	10.25a**	9.18ab	9.16ab	9.10A**
	Mean	7.02AB	6.50B	7.62A**	7.52A	
		Raw Phosphate Doses (kg da^{-1})				
90th day		0	20	40	80	Mean
S^0 Doses (kg da^{-1})	0	6.28ef	5.79ef	6.13ef	5.91ef	6.03C
	20	7.5de	7.85cde	6.93de	6.88de	7.29B
	40	9.97abc	4.34f	7.59de	7.95b-e	7.46B
	80	10.05ab	8.7a-d	10.32a	10.43a	9.87A**
	Mean	8.45A	6.67B	7.74A**	7.79A	
		Raw Phosphate Doses (kg da^{-1})				
135th day		0	20	40	80	Mean
S^0 Doses (kg da^{-1})	0	5.37e	6.14de	6.08de	7.21a-d	6.20C
	20	6.53cde	6.73b-e	7.03b-e	7.86abc	7.04B
	40	6.28cde	6.04de	7.86b-e	7.48a-d	6.92B
	80	7.05bcd	7.31a-d	8.25ab	8.80a	7.85A**
	Mean	6.31B	6.56B	7.30A	7.84A**	

**:p<0.01 *:p<0.05

Conclusion

In this study, the effect of applying S^0 with raw phosphate materials to soils on microelements (Fe, Zn, and Mn) in soils was investigated. The study was conducted as a pot experiment. According to the data obtained, an increase in the DTPA-extractable Fe, Zn, and Mn concentrations of the soils was observed under raw phosphate treatment conditions with S^0 treatment. S^0 treatment can be considered as an alternative for increasing the available Fe, Zn, and Mn concentrations in alkaline and high-lime content soils with low micro-nutrient element concentrations. However, it would be beneficial to test this through detailed field trials.

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Evaluation of different carrier materials for the shelf life of *Bacillus megaterium* RK01 using GGE biplot analysis

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Abstract

The effectiveness of microbial fertilizers varies depending on the type of microorganism used and the properties of the carrier material. The aim of this study is to reveal the relationship between the physicochemical properties of various organic and inorganic solid carriers and the shelf-life performance of the *Bacillus megaterium* RK01 strain formulated with these carriers using GGE biplot analysis.

In the study, the local strain *Bacillus megaterium* RK01 was used as the microbial inoculant. The carrier materials tested included Biochar (BC), Tea Compost (TC), Compost (C), Leonardite (L), Vermicompost (V), Imported Peat (IP), Domestic Peat (DP), Gavurdağ Peat (GP), Bentonite (B), Rock Phosphate (RP), Perlite (P), Pumice (Pu), Light Expanded Clay (LEC), and Zeolite (Z). The following properties of the carriers were analyzed: pH, electrical conductivity (EC), water holding capacity (WHC), organic carbon (OC), C/N ratio, and the content of Fe, Cu, Zn, Mn, Mg, K, Ca, P, and N. The shelf life of the RK01 strain within each carrier was monitored at room temperature by measuring the colony-forming unit (CFU) counts on days 15, 30, 60, 90, 120, 150, 180, 210, 240, 270, and 300. Additionally, the pH, EC, and moisture content of the carriers were tracked throughout the storage period. According to GGE biplot analysis, Vermicompost and Gavurdağ peat are grouped with other organic materials in terms of physical and chemical properties, providing sufficient elements necessary for microorganisms to survive. These materials show high shelf-life, stable pH and EC, and good moisture retention, making them the best choice for microbial inoculants. They exhibited different and negative characteristics in LEC, EC, and other parameters. Furthermore, GGE biplot graphs were highly effective for this study because they summarized multiple variables, revealed the main trends, showed correlations between properties, and facilitated the grouping of carrier materials, making it easier to select the best options for microbial survival.

Keywords: Phosphate-solubilizing bacterium (PSB), carrier material, shelf life, GGE biplot technique, scatter plot matrix.

Introduction

Phosphate-solubilizing bacteria (PSB) are microorganisms that solubilize phosphorus compounds in the soil, which would otherwise be unavailable to plants, making them accessible for plant uptake. In agriculture, the use of these bacteria boosts the efficiency of phosphorus fertilizers, supports plant growth, improves soil fertility, and contributes to environmental sustainability by reducing the reliance on chemical fertilizers. Choosing suitable carrier materials for microorganisms whose effectiveness has been established through greenhouse and field trials is crucial to ensure their practical applicability and to select the right material for the production of microbiological phosphate fertilizers. In general, biofertilizers formulated with carriers

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support plant growth more effectively than free-cell biofertilizers. The main reason for this is that carriers can protect functional microorganisms from soil and climatic stress factors (Daza et al., 2000; Jain et al., 2010).

Bacterial carriers are defined as solid, semi-solid, or liquid materials capable of maintaining specific bacterial populations at acceptable levels over extended periods and delivering microorganisms to the seed surface or rhizosphere. Carriers may be of organic or inorganic origin, and selective carriers specifically designed for certain microorganisms are also available (Pandey and Maheshwari, 2007). A high-quality carrier should effectively transfer viable microorganisms produced under laboratory conditions to the field (Brahmaprakash and Sahu, 2012).

An ideal carrier should possess high moisture retention capacity, be easy to process and sterilize, economical, and readily available. Additionally, it is preferable for the carrier to have good buffering capacity and high structural stability. Carrier materials should facilitate adhesion to the seed surface, must not be toxic to microorganisms, and should be able to release functional microorganisms into the soil with ease (El-Fattah et al., 2013; Stephens and Rask, 2000; Rebah et al., 2002; del Carmen Rivera-Cruz et al., 2008). According to the literature, no single carrier possesses all the characteristics required for an ideal carrier. However, carriers that incorporate many important features are considered the most suitable options (Brahmaprakash and Sahu, 2012).

The effectiveness of microbial fertilizers varies based on the type of microorganism used and the characteristics of the carrier material. As a result, numerous studies have been conducted using various organic and inorganic carriers for different microbial species. For instance, poultry manure and banana waste have been evaluated as carriers for Azospirillum, Azotobacter, and phosphate-solubilizing bacteria (del Carmen Rivera-Cruz et al., 2008); vermicast and lignite for Azotobacter chroococcum, Bacillus megaterium, and Rhizobium leguminosarum (Sekar et al., 2010); biochar derived from acacia wood and coconut shells for Azospirillum lipoferum (AZ 204) (Saranya et al., 2011); biochar and fly ash for Burkholderia sp. L2 (Tripti et al., 2022); rock phosphate, vermicompost, perlite, and bentonite for Pseudomonas fluorescens (Shariati et al., 2013); compost, peat, biogas slurry, and press mud for Bacillus cereus strain Y5, Bacillus sp. Y14, and Bacillus subtilis strain Y16 (Shahzad et al., 2017); and fly ash, soil, and montmorillonite for blue-green algae (Kaur and Goyal, 2019).

In this study, Principal Component Analysis (PCA) was employed to examine the multivariate relationships among carrier materials, their physical and chemical properties, and parameters related to shelf life. PCA is a widely used technique for reducing the dimensionality of complex datasets by transforming the data into a smaller number of principal components that capture the maximum variance (Jolliffe, 2002; Jolliffe and Cadima, J., 2016).

The objectives of this study are to determine the physical and chemical properties of various carrier materials, evaluate their potential as carriers for an alternative phosphate-solubilizing bacterium, and identify the relationship between these carriers' physicochemical properties and the performance (shelf life) of Bacillus megaterium strain RK01 in the formulated biofertilizers.

Material and Methods

Materials

In this study, a native strain of *Bacillus megaterium* RK01 was used as the microbial inoculant. The carrier materials evaluated included: Biochar (BC),Tea compost (TC), Compost (C),Leonardite (L), Vermicompost (V), Imported Peat (IP), Domestic Peat (DP), Gavurdağ Peat (GP), Bentonite (B), Rock phosphate (RP),Perlite (P),Pumice (Pu),Light expanded clay (LEC), Zeolite (Z).

The native isolate *Bacillus megaterium* RK01 was obtained from the culture collection of the Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Ondokuz Mayıs University (OMU).

In this study, imported peat, Gavurdağ peat, and local peat were used, which provide a suitable environment for bacterial survival due to their high organic matter content and water-holding capacity. Zeolites, with their high cation exchange capacity, offer mineral support for bacterial activity, while leonardite promotes microbial activity through its humic and fulvic acid content. Pumice facilitates microbial colonization with its porous structure, whereas perlite, being sterile and inert, requires additional nutrient supplementation to function effectively as a carrier. Biochar, produced from broiler poultry manure at 400°C, supports microbial retention due to its high surface area and porosity. Farmyard manure compost and vermicompost were evaluated as microbial carriers owing to their rich organic matter and microbial content. Locally sourced raw phosphate from the Mazı Mountain was included as a phosphorus source; however, due to its low solubility, its potential as a carrier is limited. Tea waste obtained from tea factories was composted using the Indore method to eliminate pathogens. Bentonite, with its high surface area and cation exchange capacity, enhances microbial retention, while lightweight expanded clay provides a porous environment conducive to microbial colonization.

Methods

Preparation of biofertilizers used in experiments

Bacterial Propagation: The bacteria stored at -80°C were streaked onto solid nutrient agar medium (containing 5 g peptone, 3 g meat extract, 10 mg $MnSO_4 \cdot H_2O$ per liter, pH = 7) and incubated at 27°C for 48 hours. After incubation, a loopful of each developed bacterial colony was transferred into 250 mL Erlenmeyer flasks containing nutrient broth. The broth cultures were incubated on a shaker set at 91 rpm and 27°C for 24 hours to allow for aerobic bacterial growth. The resulting bacterial suspensions were then diluted with sterile distilled water and adjusted to a final concentration of 10^8 CFU/mL using spectrophotometric measurements.

Preparation of Carrier Materials: The 14 carrier materials were dried and crushed, then sieved to obtain particle sizes between 0.2–0.5 mm. To eliminate contamination, all materials were sterilized in an autoclave at 121°C for 3 hours.

Inoculation: The carrier materials were mixed with bacterial cultures propagated in nutrient broth at a ratio of 100 mL per kilogram of carrier. The mixing was performed manually using sterile gloves. The materials were moistened to 50% of their water-holding capacity. The prepared inoculated carriers were then incubated at room temperature (25°C). These materials were used for the shelf-life experiments.

Shelf life studies

To determine the shelf life of strain RK01 at room temperature, the population density in each carrier was examined by measuring the colony-forming units (CFU) at 15, 30, 60, 90, 120, 150, 180, 210, 240, 270, and 300 days. For the CFU calculation, 1 g of inoculant was suspended in 9 mL of sterile water. To ensure complete release of the strain from the carriers, the test tubes were shaken at 150 rpm on a rotary shaker for 30 minutes. Subsequently, the solutions were serially diluted, and 100 µL from the final dilution was plated onto nutrient agar plates. Each dilution was performed in triplicate. All plates were incubated at 28 ± 2°C for 2–3 days. The microbial colonies formed on each petri dish were counted, and the inoculant's Log CFU g^{-1} value was calculated.

Methods used to determine the properties of carrier materials

The pH and electrical conductivity (EC) of organic carrier materials (biochar, tea compost, compost, leonardite, vermicompost, imported peat, local peat, Gavurdağ peat) were measured potentiometrically in a 1:10 (w/v) material-to-sterile water suspension. Moisture content was determined by drying the samples at 105°C, and organic matter (OM) was measured using the dry combustion method. In samples combusted dry, the concentrations of Ca, Mg, Fe, Cu, Zn, and Mn were analyzed by Atomic Absorption Spectroscopy (AAS). Phosphorus content was determined by the molybdenum blue phosphoric acid method, and nitrogen content was analyzed using the Kjeldahl method (Kacar, 1990). For inorganic materials (zeolite, pumice, perlite, raw phosphate, bentonite, lightweight expanded clay), pH and EC were measured potentiometrically in a 1:1 (w/v) soil-to-sterile water suspension (Bayraklı, 1987). Moisture content was determined by drying at 105°C. Organic matter was quantified using the modified Walkley-Black method (Jackson, 1958). Nitrogen content was measured by the Kjeldahl method (Kacar, 1994). Exchangeable cations were extracted with 1 N ammonium acetate (Sağlam, 1997). Phosphorus content was extracted with 1 N $NaHCO_3$ (Kacar, 1994). Micronutrient levels (Fe, Cu, Zn, Mn) were extracted with DTPA following Lindsay and Norvell (1978) and quantified using ICP analysis (Sağlam, 1997).

Statistical analysis

All statistical analyses were performed using JMP 11 software (SAS Institute, Cary, NC, USA). Principal Component Analysis (PCA) was applied to evaluate the relationships between the physical and chemical properties of carrier materials and microbial shelf life. The PCA was conducted to reveal the multivariate structure of the general physical and chemical characteristics of the carrier materials, thereby statistically visualizing the similarities, groupings, and characteristic differences among the materials. Additionally, PCA was performed to examine the effect of pH, electrical conductivity (EC), and moisture parameters on the microbial shelf life of the carrier materials. In each analysis, the relevant parameter, along with other properties of the carrier materials and microbial shelf life data, was evaluated. Prior to all PCA analyses, the data were standardized (mean = 0, standard deviation = 1), and the analyses were carried out based on the correlation matrix. Component selection was made according to Kaiser's criterion (eigenvalue > 1), and components explaining a significant percentage of the total variance were considered. The obtained component loadings and biplot graphs were used to visualize both the effects of parameters on microbial shelf life and the physicochemical characterization of the carrier materials.

Results and Discussion

The physicochemical properties of the carrier materials used in the biofertilizer formulation are presented in Table 1. Gade et al. (2014) stated that the physicochemical characteristics of carriers can significantly influence the survival and viability of microorganisms.

The pH values of the carrier materials ranged from 4.84 to 10.42. The lowest pH was observed in leonardite, while the highest was in biochar. Leonardite (4.84), imported peat (5.18), tea compost (6.13), and vermicompost (6.30) were acidic; local peat (7.08) and Gavurdağ peat (7.48) were neutral; and lightweight expanded clay (8.07), perlite (8.33), compost (8.34), rock phosphate (8.44), zeolite (8.47), bentonite (9.61), and biochar (10.42) had alkaline pH values. pH plays a crucial role in microbial populations (Deng et al., 2015). Generally, pH values close to neutral have been reported to support the survival and viability of many microbial inoculants (Arora et al., 2008; Sahu et al., 2016). Slightly alkaline or neutral conditions are often preferred for bacterial and fungal growth compared to acidic environments (Marstorp et al., 2000; Rousk et al., 2009).

Table 1. Some properties of carrier materials

	pH	EC dS/m	WHC %	OC %	C/N	Fe ppm	Cu ppm	Zn ppm	Mn ppm	Mg ppm	K ppm	Ca ppm	P ppm	N %
BC	10.42	7.505	103	35.11	14.4	1736	69.57	605.0	850.5	10814	43274	9392	19497	2.441
TC	6.13	3.540	301	45.62	9.5	901.8	10.43	28.81	438.7	1376.1	19856	1613	2554	4.801
C	8.34	2.440	230	23.76	12.3	1902	10.44	50.24	182.1	2516	7931	36804	4203	1.936
L	4.84	1.453	85	18.63	28.8	4339	2.814	9.335	101.6	865.0	776.9	7654	391.5	0.647
V	6.30	5.365	235	34.50	14.1	3732	16.03	73.09	54.64	3193	9145	8425	4664	2.451
IP	5.18	1.050	699	46.36	37.9	1676	20.38	12.80	11.98	1691	1540	17352	589.5	1.224
DP	7.08	2.690	146	21.15	17.8	9116	4.529	30.47	88.17	1060	1695	34504	795.5	1.190
GP	7.48	1.817	100	28.23	24.0	4243	7.007	35.19	57.79	2391	1061	25912	451.2	1.175
B	9.61	0.809	179	0.132	-	4.572	0.730	0.940	3.021	30.95	188.5	896.0	41.91	-
RP	8.44	0.543	14	0.182	-	0.532	5.518	1.561	0.212	3.784	32.50	262.0	1236	-
P	8.33	0.191	121	0.020	-	1.520	0.087	0.645	0.170	1.261	64.00	398.5	199.1	-
Pu	8.75	0.446	20	0.028	-	5.093	0.105	0.200	3.858	2.607	103.0	1048	241.0	-
LEC	8.04	1.259	6	0.014	-	2.432	0.070	0.266	0.431	26.83	22.00	1094	251.4	-
Z	8.47	0.471	39	0.237	-	4.694	0.157	1.338	1.463	8.410	645.0	952.0	83.81	-

Biochar(BC),Tea compost(TC), Compost(C),Leonardite(L), Vermicompost(V), Imported Peat(IP), Domestic Peat (DP), Gavurdağ Peat (GP), Bentonite(B), Rock phosphate(RP),Perlite(P),Pumice(Pu),Light expanded clay(LEC), Zeolite(Z), electrical conductivity(EC), water-holding capacity(WHC)

The EC values of the materials ranged from 0.191 to 7.505 dS/m. The EC values of the materials, in descending order, were as follows: biochar > vermicompost > tea compost > Gavurdağ peat > local peat > compost > leonardite > imported peat > bentonite > lightweight expanded clay > rock phosphate > pumice > zeolite > perlite. The EC of carrier materials indicates the concentration of soluble salts, which can significantly affect the activity and survival of microbial inoculants (Parveen et al., 2023; Zayed, 2016).

High water-holding capacity (>50%) is a desirable feature in carrier materials to support optimal bacterial growth and reproduction (Shahzad et al., 2017; Sahu et al., 2016; Mahdi et al., 2010). In this study, the water-holding capacities of the carrier materials ranged from 6% to 699%. This wide variation highlights the potential of most materials—except lightweight expanded clay, rock phosphate, pumice, and zeolite—as suitable carriers for biofertilizer production. Moisture content in carrier materials can have a significant impact on the survival and longevity of the inoculant (Sohaib et al., 2020; Zayed, 2016). In general, dry formulations with low moisture content may extend inoculant survival for longer periods and at higher temperatures, thereby reducing the need for refrigeration and lowering marketing and maintenance costs (Melin et al., 2006). This is likely because inoculants in low-moisture carriers can remain inactive, more resistant to environmental stresses, and less susceptible to contamination (Zayed, 2016). In this study, all carrier materials were moistened to 50% of their water-holding capacity.

In general, carrier materials with high organic matter (or organic carbon) content can increase the chance of survival of bacteria and the effectiveness of bio-formulations by supporting the growth and proliferation of microbial inoculants (Itelima et al., 2018). In this study, the organic carbon (OC) content of the carrier materials ranged from 0.014% to 46.36%. Among the materials used, eight were of organic origin (biochar, tea compost, compost, leonardite, vermicompost, imported peat, local peat, Gavurdağ peat) and six were of inorganic origin (bentonite, rock phosphate, perlite, pumice, lightweight expanded clay, zeolite). As expected, the highest OC values were observed in the organic materials. Among them, imported peat had the highest OC content, followed by tea compost, while the lowest OC content was found in leonardite.

Carrier materials with good physicochemical properties can also serve as nutrient sources, enhancing the survival of microorganisms (El-Fattah et al., 2013). In general, organic carriers are richer in macro- and micronutrients compared to inorganic ones, making them more suitable for microbial growth. These nutrients play key roles in processes such as carbohydrate metabolism (Shahzad et al., 2017), protein synthesis, enzyme activation, and other vital stages of growth for microbial inoculants (Pandey and Maheshwari, 2007). In this study, the Fe content of carrier materials ranged from 0.532 to 4339 ppm, with the lowest in rock phosphate and the highest in leonardite. Cu content varied between 0.070 and 77.41 ppm, with the lowest found in lightweight expanded clay and the highest in biochar. Zn levels ranged from 0.2 to 605 ppm, with the lowest in pumice and the highest in biochar. Mn content ranged from 0.170 to 850 ppm, with the lowest levels in perlite and the highest in biochar. Mg levels ranged from 1.261 to 7977 ppm, with the lowest in perlite and the highest in biochar. K content ranged from 22 to 23,690 ppm, the lowest being in lightweight expanded clay and the highest in biochar. Ca content ranged between 262 and 36,804 ppm, with rock phosphate having the lowest and compost the highest concentration. P content ranged from 41.91 to 19,497 ppm, the lowest in bentonite and the highest in biochar. N content ranged from 0.647% to 4.801%, with the lowest in leonardite and the highest in tea compost (see Table 1). As inorganic materials are primarily mineral in structure, they generally do not contain nitrogen. Therefore, nitrogen content was not determined for bentonite, rock phosphate, perlite, pumice, lightweight expanded clay, and zeolite in this study (Table 1).

Shelf life studies

A noticeable decrease in shelf-life values was observed over time for all carrier materials. A particularly rapid decline occurred between days 180 and 300. Initially (in the first months), shelf-life values were relatively high, around 11–12 log CFU, indicating that the materials were relatively stable at the beginning. Around day 180, the shelf-life of many materials dropped to 7–9 log CFU. At this stage, microbial activity, oxidation, or chemical degradation may have accelerated. After day 300, shelf-life values began to stabilize at around 5–6 log CFU, suggesting that the degradation process had slowed down or that the factors affecting shelf life had reached equilibrium. At day 360, materials such as vermicompost and Gavurdağ peat still maintained viable cell counts of approximately 6–7 log CFU, In contrast, materials like rock phosphate and leonardite showed lower counts around 4 log CFU. This indicates that some carrier materials provided better protection, while others depleted shelf life more rapidly (Figure 1a).

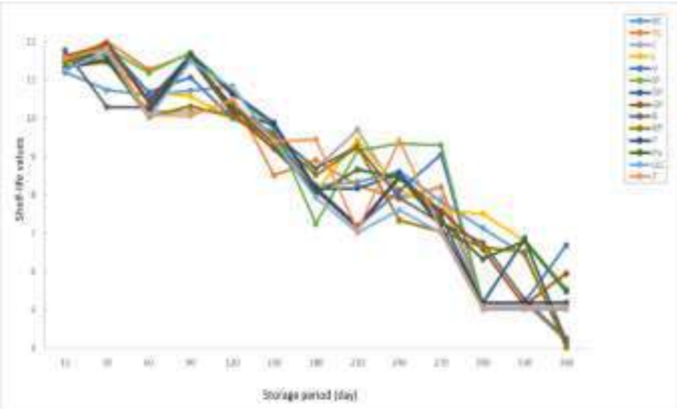
A good carrier material plays a vital role in inoculant effectiveness by supporting the survival of the desired number of physiologically active strains from storage to field application (Li et al., 2023). The survival ability of Bacillus megaterium in press mud, coconut coir, vermicompost, and lignite was evaluated over a period of 240 days at room temperature. The results showed that press mud maintained Bacillus megaterium populations at higher levels for the longest duration, followed by vermicompost, lignite, and coconut coir. On day 240, the population of Bacillus megaterium in press mud was recorded as 2.0×10^7 cfu/g. Researchers noted that this carrier had excellent moisture retention capacity and, due to its structure enriched with enzymes, provided a favorable environment for microorganisms (Shruthi et al., 2015). Phiromtan et al. (2013) reported that bacterial population density decreases over time due to moisture and nutrient (OM, N, P, K, etc.) deficiencies in the carrier, bacterial activities, and the shift from the logarithmic phase to the stationary phase during the incubation period under storage conditions.

During the shelf-life studies, the pH values of the carrier materials were also monitored. Trends in pH changes can serve as important indicators of microbial stability, the chemical properties of the carrier material, and the quality of the microbial fertilizer throughout the shelf-life period.

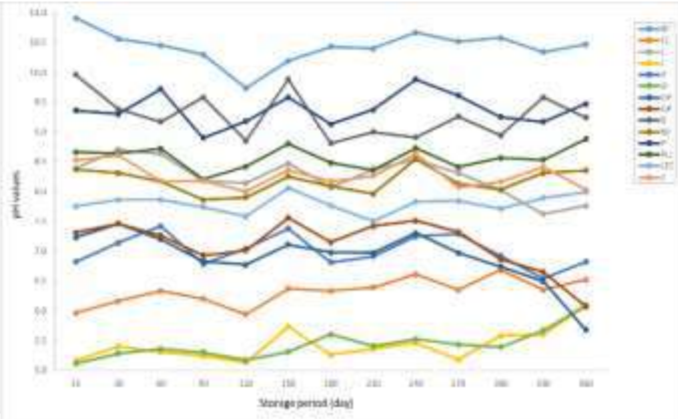
When examining the pH values, changes were observed in the materials from day 15 to day 360. However, these changes were not significant enough to alter the pH classification of the materials. Materials such as Biocar, bentonite, rock phosphate, and zeolite showed a tendency for pH to decrease compared to day 15. In contrast, materials like tea compost, leonardite, and imported peat exhibited an increasing pH trend, while compost, vermicompost, local peat, Gavurdağ peat, perlite, pumice, and lightweight expanded clay displayed fluctuating pH values (Figure 1b). The increase in pH may be related to the metabolic activities of microorganisms or the buffering capacity of the carrier material. Some microorganisms can produce basic compounds such as ammonia (NH_3) or amines, which can raise the pH. Conversely, a decrease in pH may be associated with the breakdown of organic compounds or the release of acid-soluble minerals. Some bacteria (e.g., Bacillus spp.) can produce organic acids, which acidify the environment.Li et al. (2023) reported that in their study, the initial pH of the carrier material consistently decreased until day 30, then slightly fluctuated or increased until the end of the storage period, possibly induced by enzyme secretion from the strains within the carrier materials.

During the shelf-life studies, the EC values of the carrier materials were also monitored. EC is a parameter that indicates the concentration of dissolved salts in a medium. Changes in EC over the shelf-life period occur due to processes such as microbial activity, mineral solubilization, and the degradation of organic compounds. EC variations provide important insights into the stability of the microbial fertilizer and the solubility of the carrier material. Preventing excessive fluctuations in EC is critical for both microbial viability and fertilizer effectiveness during long-term storage. When examining EC values, changes were observed in the materials from day 15 to day 360. In Biocar, EC showed an increasing trend compared to day 15, while materials such as compost, vermicompost, local peat, and pumice showed a decreasing trend. Materials like tea compost, leonardite, imported peat, Gavurdağ peat, bentonite, rock phosphate, perlite, lightweight expanded clay, and zeolite exhibited fluctuating EC values (Figure 1c). Minerals or soluble nutrients (e.g., potassium, calcium, magnesium, phosphate) in the microbial fertilizer may dissolve over time, increasing the EC. As microorganisms break down organic compounds, inorganic ions may be released, which can also raise EC. Water loss during storage (e.g., drying or evaporation) can concentrate salts in the solution, leading to increased EC. Rapidly growing bacteria can consume nutrient ions quickly, causing a decrease in EC. Fermentation or a reduction in microbial activity may result in a decrease in EC. As microorganisms transition from the growth phase to the stationary phase, ion consumption may stabilize.

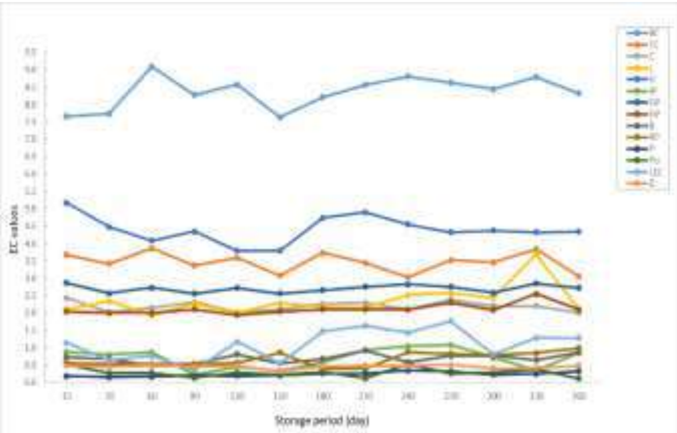
Moisture content of the carrier materials was also monitored throughout the shelf-life study. Moisture is a key factor in microbial fertilizers and carrier substrates, influencing microbial viability, chemical reactions, and the physical stability of the formulation. Changes in moisture content over time can reflect various biological and physicochemical processes occurring during storage. Excessive moisture loss may reduce microbial survival, while excessive moisture gain can disrupt the microbial balance and promote undesirable microbial activity. Therefore, maintaining moisture stability is critical for ensuring both the longevity and effectiveness of microbial inoculants. Across the storage period (day 0 to day 360), moisture content generally showed a decreasing trend (Figure 1d). This decrease was more pronounced in inorganic carriers compared to organic ones. Similar results were reported by Li et al. (2023), who observed a gradual decline in moisture content for all carriers tested as storage duration increased.



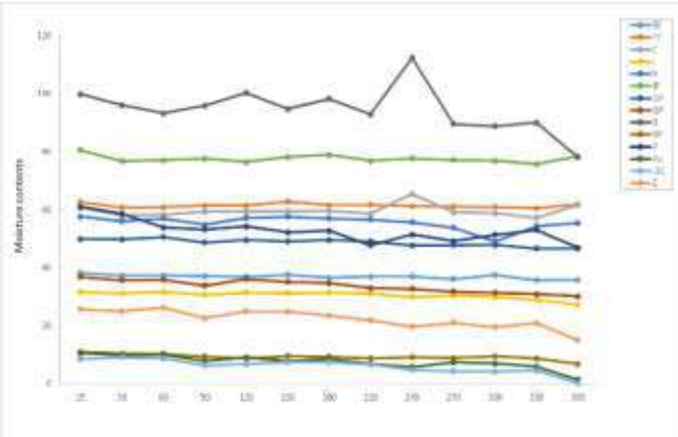
a)Shelf-life of Different Carrier Materials Over Time (log CFU)



b)pH Changes of Carrier Materials During Shelf-life Study



c)EC Changes of Carrier Materials During Shelf-life Study

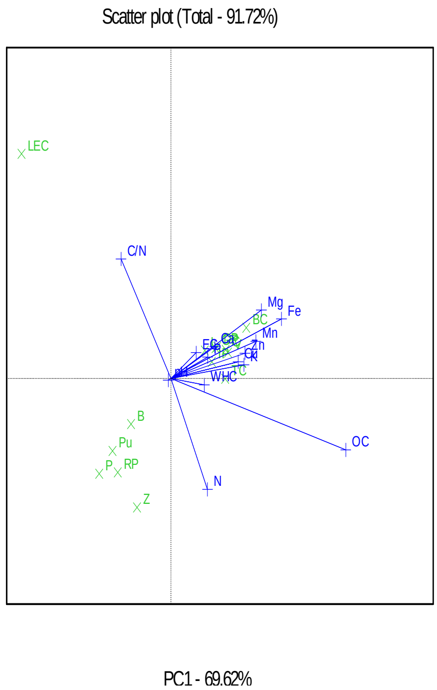


d)Moisture Content Changes of Carrier Materials During Shelf-life Study

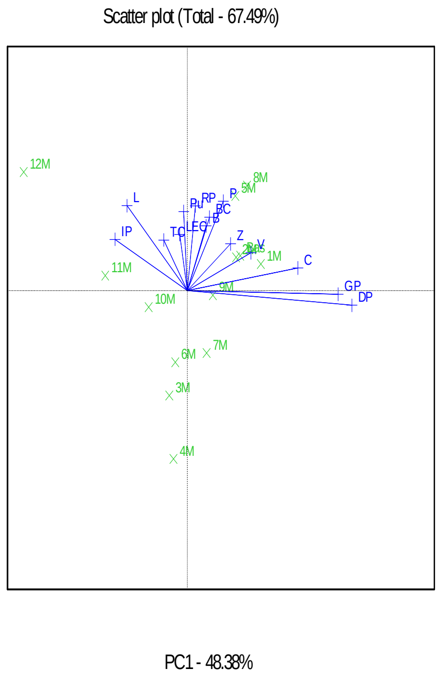
Figure 1. Biochar(BC),Tea compost(TC), Compost(C),Leonardite(L), Vermicompost(V), Imported Peat(IP), Domestic Peat (DP), Gavurdağ Peat (GP), Bentonite(B), Rock phosphate(RP),Perlite(P),Pumice(Pu),Light expanded clay(LEC), Zeolite(Z), electrical conductivity(EC), water-holding capacity(WHC)

GGE biplot analysis

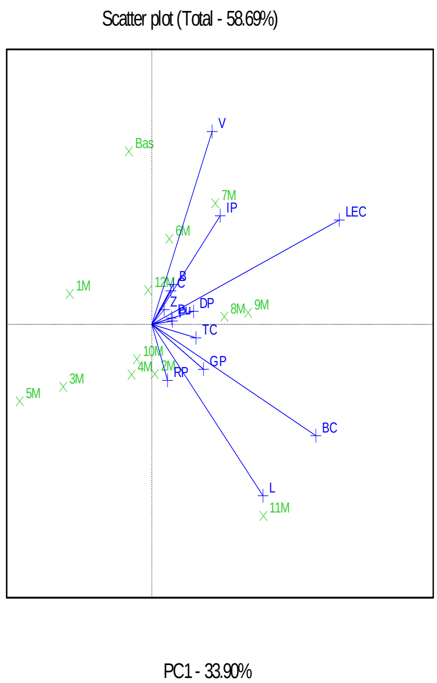
To evaluate the contribution of selected physicochemical properties of carrier materials to the survival performance of the bacterial strain, and to better understand the relationships between carrier type, pH, EC, and moisture content over the storage period, a principal component analysis (PCA) was performed.



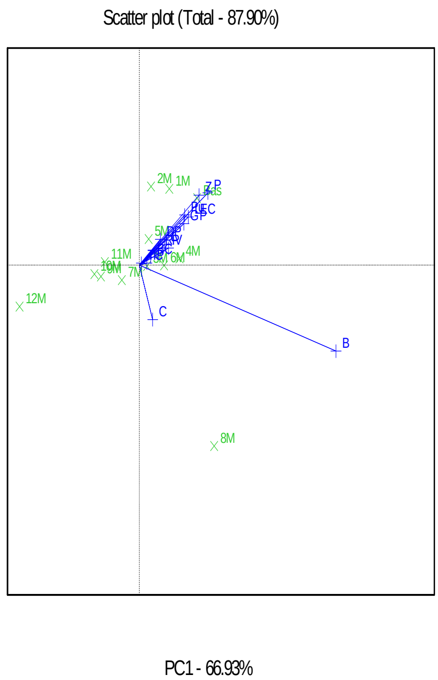
a) PCA analysis of multivariate characterization of carrier materials based on their physical and chemical properties



b) PCA analysis of the relationship between pH value of carrier materials and microbial shelf life



c) PCA analysis of the relationship between EC value of carrier materials and microbial shelf life



d) PCA analysis of the relationship between moisture content of carrier materials and microbial shelf life

Figure 2. Principal component analysis (pca) results

Figure 2a presents the multivariate characterization of the carrier materials based on their physical and chemical properties, visualized through PCA. The analysis results show that the first principal component (PC1) explains 69.62% of the total variance, while the second principal component (PC2) accounts for 22.18%, resulting in a high cumulative variance explanation rate of 91.72%. This high explanatory power indicates that the model effectively captures the specific physical and chemical properties of the carrier materials and the relationships among these properties. The angular relationships between variable vectors reflect fundamental correlations. For example, the narrow angle between the Mn and Zn vectors indicates a strong positive correlation between these two variables; the approximately 90° angle between EC and OC suggests no significant correlation between these parameters; and the wide angle between N and the C/N ratio reflects a negative correlation.

The LEC carrier (positioned alone in the upper left) is located far from all other samples, indicating that LEC possesses properties that are very different from those of the other carriers. Since it is oriented in the opposite direction to variables such as OC, N, Fe, Zn, Mn, and Mg, it can be inferred that these properties are low in LEC. The Z, RP, Pu, P, and B carriers (clustered in the lower left) are located close to each other, showing that they share similar characteristics. This group is negatively associated with variables such as N and OC, meaning that the values of these variables are low in these samples (Table 1). The TC, BC, C, L, V, IP, DP, and GP carriers (densely clustered in the upper right) are highly similar to each other and positively associated with variables such as Fe, Zn, Mn, Mg, OC, and N. This indicates that these materials contain these elements in high amounts (Table 1). Furthermore, since they are highly positively loaded along the PC1 component, they exhibit significant differences in terms of the variance explained by this component.

Figure 2b was created to evaluate the relationship between the pH values of carrier materials at different time points and their shelf life (microbial population). The PCA results in Figure 2b show that PC1 explains 48.38% of the variance, while PC2 contributes 19.11%, resulting in a cumulative variance explanation of 67.49%. The narrow angle between BC and B confirms a strong positive correlation between these carriers in terms of pH values. The approximately 90° angle between Pu and GB indicates no significant correlation, while the wide angle between IP and DP indicates a negative correlation in terms of pH values. It is observed that there is a strong positive relationship among the carriers DP, GB, and C in the first group; Z, V, EC, RP, P, BC, B, and TC in the second group; and L and IP in the third group. On the other hand, in terms of pH, the best months were determined as the 9th month for the first group (DP, GB, and C), the 2nd, 5th, and 8th months for the second group (Z, V, LEC, RP, P, BC, B, and TC), and the 11th month for the third group (L and IP). Additionally, the 12th month was found not to stand out in any of the properties examined in the study.

Figure 2c was created to evaluate the relationship between the EC values of carrier materials at different time points and their shelf life (microbial population). Similarly, the PCA biplot in Figure 2c shows that PC1 (33.90%) and PC2 (24.79%) together account for 58.69% of the total variance, highlighting the dominant relationships between shelf life and the EC values of the carrier materials. The narrow angle between BC and DP indicates a strong positive correlation, whereas the wide angle between B and RP indicates a negative correlation. Furthermore, examination of the plots reveals that the carrier materials are grouped into four distinct clusters. A strong positive relationship is observed among BC, L, GP, and RP in the first group; LEC and IP in the second group; V in the third group; and Z, B, and DP in the fourth group. On the other hand, the 11th month was identified as the most suitable selection period for carriers in the first group, while the 7th and 9th months were optimal for carriers in the second group. The 5th month was found not to stand out in terms of EC values for any of the carriers examined in the study.

Figure 2d was created to evaluate the relationship between the moisture content of carrier materials at different time points and their shelf life (microbial population). The PCA scatter plot in Figure 2d shows that PC1 explains 66.99% of the variance, while PC2 accounts for 20.96%, resulting in a combined explanatory power of 87.90%. This indicates that the model effectively represents the relationships between moisture content and shelf life of the carrier materials. Examination of the plots reveals that the characteristics are grouped into two distinct clusters. A strong positive relationship is observed between B and C in the first group, and among Z, V, LEC, RP, P, BC, B, TC, L, and IP in the second group. On the other hand, the 8th month was identified as the most suitable selection period for the characteristics in the first group (B and C), In contrast, the 1st and 2nd months were optimal for the characteristics in the second group. Additionally, the 12th month was found not to stand out for any of the carriers examined in the study.

Saranya et al. (2011) observed the positive effect of N while testing the shelf life of soil inoculant Azospirillum lipoferum with various biocars. Hale et al. (2015) reported that the chemical properties of biochar, especially nitrogen content and pH, influence the initial microbial density and shelf life of the product; however, after incorporation into the soil, physical properties such as biochar's surface area, pore size, and water-holding capacity become more critical for bacterial survival in the soil. On the other hand, Jindo et al. (2012) reported a negative correlation between the C:N ratio and bacterial biomass in biochar-compost mixtures. Li et al. (2023) emphasized that the performance of carrier materials is shaped not by a single factor but by the interaction of multiple physicochemical parameters. Their study highlighted the importance of high calcium (Ca) and sulfur (S) content, water-holding capacity (WHC), and optimal pH values of carrier materials, suggesting that adjusting these parameters before the selection or production of commercial products would be beneficial. Shabir et al. (2023), based on path analysis results, stated that the shelf life of rhizobial bacteria is largely and positively influenced directly by total carbon (TC), manganese (Mn), specific surface area (SSA), pore size, ketonic carbon (C=O), and carboxyl carbon (O-C=O) functional groups.

Conclusion

The aim of this study is to reveal the relationship between the physicochemical properties of various organic and inorganic solid carriers and the shelf-life performance of the Bacillus megaterium RK01 strain formulated with these carriers using GGE Biplot analysis.

In our study, LEC stands out as a unique carrier with low nutrient and organic matter contents compared to all others. Carriers such as Z, RP, Pu, P, and B have lower nutrient levels but share similar traits. Conversely, carriers like TC, BC, C, L, V, IP, DP, and GP contain high levels of macro- and micronutrients as well as carbon.

Based on the results, the most suitable carrier materials for maintaining microbial survival and stability are vermicompost and Gavurdağ peat. These materials show high shelf-life, stable pH and EC, and good moisture retention, making them the best choice for microbial inoculants." Furthermore, GGE Biplot graphs were highly effective for this study, as they summarized multiple variables, revealed the main trends, showed correlations between properties, and facilitated grouping of the carrier materials, making it easier to select the best options for microbial survival.

In this study, more emphasis was placed on the chemical properties of the carriers, with water holding capacity (WHC) being the only physical property considered. Carriers with high organic matter and moisture retention capacity, low EC values, and neutral pH were evaluated as suitable carriers. However, in addition to these, carriers should also possess some essential physical properties such as adequate air permeability, a stable structure, and porosity that allows microorganisms to adhere to the surface. Including these properties in future studies would enable a more accurate selection of carriers.

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Study of the Soil Cover Structure of the Gobustan Massif

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Abstract

Gobustan is a region within Azerbaijan's Shirvan province, situated in the eastern and southeastern foothills of the Greater Caucasus, in the eastern part of Azerbaijan. According to modern physical-geographical zoning, Gobustan is classified as a separate area, stretching 80 km from east to west and 100 km from north to south. The district lies east of Shamakhi, 101 km from Baku. The terrain of Gobustan is mountainous and complex, featuring valleys, ravines, and rocks. Geographically, the mountain slopes are categorised into plateaus, hilly terrains, and plains, with the plateau occupying Gobustan's northwest. Clay karst has developed in the Adjidara area, forming widespread karst landscapes. Winds, precipitation, and mud volcanoes have shaped a major part of the region's relief. Geologically, Gobustan is rich in oil and gas. The mud volcanoes are a natural sign of this. Gray-brown saline and various gray-brown soils are prevalent here. Soil profiles were established, and individual types of the structures of the soil cover (SSC) were identified within Gobustan. Using the method of relief plasticity, the SSC of the Gobustan massif was determined and mapped at a scale of 1:100,000. Identified types include the dendritic in the foothill area, the radial-circular, and the dendritic of volcanic origin. It was determined that the formation of SSC and the soil properties are influenced by the exposure of slopes specifically, the contrasting conditions of the northwestern shaded and southeastern sunlit parts of the relief. Mountain gray-brown and saline soils of the southeastern sunlit slopes display reduced humus-accumulative horizons (AY = 15–20 cm), humus content (1.0–1.5%), and absorbed bases (15–18 mmol-eq), alongside increased salinity (1.35–2.67%), pH (8.5–9.0), weakened granulometric structure (<0.01 mm = 38–45%; <0.001 mm = 35–41%), and accelerated erosion.

Keywords: Gobustan, structures of soil cover, relief, exposure of slopes, soil properties.

Introduction

Gobustan is one of the districts of the Shirvan Province of Azerbaijan and is located in the eastern and southeastern foothills of the Greater Caucasus, in the eastern part of the Republic of Azerbaijan. According to the modern physical-geographical classification of Azerbaijan, Gobustan itself is a separate physical-geographical region. Gobustan stretches 80 km from east to west and 100 km from north to south. The Gobustan District is located to the east of Shamakhi, 101 km from Baku.

The Gobustan massif is a mountainous zone with a complex terrain represented by valleys, ravines, and cliffs. According to geographical classification, mountain slopes are divided into three areas: plateaus, hills, and plains. The mountain plateau covers the northwestern part of Gobustan. In the mountains near Adzhidere,

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clay karst has developed. Therefore, karst landscapes are widespread here. Wind, precipitation, and mud volcanoes played a significant role in shaping the terrain of Gobustan. From a geological point of view, Gobustan is rich in oil and gas. Their natural indicators are mud volcanoes. Located within the district are the Dzhayirli, Shorsulu, Sheikhsyarli, and other mud volcanoes. The region has reserves of various construction materials (limestone, sand, gravel, volcanic ash, gypsum, shale). A typical karst landscape is widespread. Wind, precipitation, and mud volcanoes play a significant role in forming the landforms of Gobustan.

Out of the 4,000 plant species growing in Azerbaijan, only 470 species are found here in Gobustan. Most of them are flowering plants. For example, black currant, wormwood, carnation, fig, rosehip fruits, etc. Xerophytic plants are widespread. There are drought-resistant shrubs – pomegranate, wormwood, fig, blackberry, rosehip, grape, and others. It should be noted that such shrubs are adapted to growing on rocky cliffs. This is because they easily absorb water droplets falling on the rocks from small showers. The vegetation cover is divided into dry steppe, semi-desert, and desert types. A typical variant of dry steppe vegetation is the wormwood-ephemeral formation, associated with light brown, slightly solonetzic soils. However, due to cultivation, secondary ephemeral communities develop.

Semi-desert vegetation mainly develops on deluvial, alluvial plains and in the coastal zone on young surfaces that recently emerged from the sea. The edifier of the semi-desert is xerophilous semi-desert wormwood, with significant participation of pseudo-turf grasses and other ephemerals.

Drought-resistant plants include pomegranate, fig, bird grape, and so on. These shrubs are adapted to growing on rocks, as they can easily absorb water droplets that fall onto rocks during light rainfall or dew.

Material and Methods

The climate is mainly semi-arid. Winters are mild, and summers are hot. The rainy season is early spring and late autumn. The annual amount of precipitation is 250 mm. The western part of Gobustan receives more moisture in autumn and spring than the eastern part, as the Kura Lowland covers the western portion. The highest average temperature is observed in July (32 °C), and the lowest in January (–1.6 °C).

The soil cover of Gobustan is diverse – light brown saline soils are widespread in the eastern part, and varieties of gray-brown soils are present in the northwest.

Both desk and field research were conducted. Samples of breccia were collected from the base and crater of mud volcanoes in the Pirekeshkul area. These are coarse-fragmental rocks consisting of cemented angular fragments of various rocks. Volcanic breccia, like lava flows, spreads radially from the crater. In general, the products of mud volcanism consist of solid, liquid, and gaseous components.

The structure of the soil cover (SSC – soil cover structure) is the heterogeneity of the soil cover within zones, subzones, and provinces, caused by natural and anthropogenic soil-forming factors. V.M. Fridland (1972) did not emphasise this, but these factors are highly ecological and systematic, as they clearly organise the complex state of the soil cover based on a set of patterns and special concepts.

In our opinion, the formation of soil cover structures is influenced by climate, zonality, and relief. The heterogeneity of parent rocks, groundwater, and other factors is also important. Some characteristic manifestations of zonality and relief in soil formation are reflected in the work of V.R. Volobuev.

Gobustan is composed of a complex of sedimentary deposits: sands, sandstones, clays, and limestones of Upper Cretaceous–Cenozoic age. In the western part, clay rocks and their weathering products are widely distributed, which are distinguished by significant gypsum content and salinity. There are mud volcanoes, the eruption products of which cover significant areas of Gobustan. The eastern lowland part is covered with sands and shell limestone. Characteristic landforms include a cellular dissected surface of limestones and sandstones, hummocky and dune sands, ravines, gullies, and other forms.

In Gobustan, a unified groundwater table is observed only in the eastern lowland part. Due to the rising level of the Caspian Sea and the influence of oil wastewater, the groundwater level has risen to 0.5–1.5 m above the soil surface. As a result of flooding, some land areas are in a severe ecological situation.

Results and Discussion

The described soils are mainly formed on the carbonate weathering crust. To characterise dark gray-brown soils, we present a description of a profile laid on the northwestern shaded exposure of the Gobustan massif. A description of the profile indicates that the most characteristic features of dark grey-brown soils are a prevalence of warmer hues in their coloration, a subangular blocky structure in the sub-ploughing B1 horizon, the presence of carbonate formations within the illuvial horizon, and a high degree of clay enrichment, particularly in the middle portion of the profile.

As the tabulated data show, dark gray-brown soils are characterised by humus content ranging from 4.3–5.0%, with deeper penetration of humus into the soil profile. Nitrogen values in the upper horizon of the soil vary from 0.29–0.42%. A characteristic indicator of the genesis of these soils is the C:N ratio. The C:N ratio ranges from 6.7–8.6, which is remarkably close to the values noted above for brown carbonate soils. Also characteristic of the described soils is the presence of carbonates from the surface soil layer. The data on absorbed bases show a high saturation of dark gray-brown soils with bases.

Ordinary gray-brown soils are associated with elevations from 300 to 400 m. These soils develop under ephemeral-wormwood vegetation. The parent rocks for ordinary gray-brown soils are deluvial-proluvial carbonate loams.

№ of section	Depth, cm	Humus, %	Nitrogen, %	$CaCO_3$, %	pH aqueous suspension	Sum of absorption bases, mmol-ekv	Dense residue, %	Granulometric composition, %	
								<0,001mm	<0,01mm
				Northwest (darkened) exposure					
5	AU 0-22	3,20	0,21	10,7	7,5	35,0	0,152	23,60	66,00
	A/B 22-46	1,50	0,12	9,1	7,9	30,5	0,187	30,80	70,80
	B 46-72	0,97	0,08	11,6	8,0	32,4	0,183	32,80	71,00
	B/C 72-110	0,58	t.olm	12,8	8,1	30,4	0,150	31,20	74,40
	C 110-145	0,41	"—"	20,7	8,2	23,3	0,174	28,40	69,00
6	AU 0-18	2,69	0,18	1`8,8	7,3	37,5	0,150	33,20	74,80
	A/B 18-40	1,30	0,09	18,8	7,7	31,4	0,132	36,80	76,40
	B 40-75	0,65	0,05	12,1	7,8	35,6	0,176	37,20	78,40
	B/C 75-108	0,36	t.olm	14,0	7,8	32,8	0,245	38,40	77,60
				South-east (solar) exposure					
7	AY 0-15	1,76	0,10	12,4	8,0	32,9	0,146	19,20	55,20
	A/B 15-28	0,83	0,06	14,9	8,2	34,7	0,152	26,40	58,60
	B 28-45	0,54	0,05	18,9	8,1	32,4	0,134	23,20	56,40
	CI 45-72	0,31	t.olm	20,0	8,3	27,4	0,340	18,80	50,00
	CII 72-90	0,24	"—"	26,5	8,2	22,3	0,438	16,00	35,20
8	AY 0-10	1,55	0,12	14,6	7,8	22,5	0,170	17,20	48,80
	B 10-32	0,75	0,06	18,9	7,8	21,5	0,192	24,40	50,40
	B/C 32-60	0,31	t.olm	21,2	8,3	23,2	0,365	18,56	53,20
	CII 60-85	0,31	"—"	27,4	8,1	19,1	0,536	19,00	49,24

Due to the relative dissection and high drainage of the area where ordinary gray-brown soils are distributed, the groundwater lies deep and does not play a significant role in the soil-forming process. Among cultivated soils, solonetzic varieties of gray-brown soils are noted, mainly associated with saucer-shaped microdepressions.

As a typical representative of ordinary gray-brown soils, we present a description of a profile laid on the southeastern exposure of the Gobustan massif. As the profile descriptions show, the characteristic features of the morphological structure of ordinary gray-brown soils are a relatively large thickness of the humus horizon, a nutty structure of the B horizon, well-expressed carbonate illuviation, locally noticeable biological activity, and effervescence from the surface horizon. Ordinary gray-brown soils, compared to dark gray-brown soils, are characterised by lower humus content. Its amount in the upper soil layer ranges from 2.7–3.2%, and in the middle horizon from 1.1–0.28%. The C:N ratio does not show much difference, though it has slightly lower values – within the A horizon, it ranges from 5.1 to 8.7. Increased carbonate content was noted – 3.43–16.4%, increasing with depth, which is largely explained by illuviation of carbonates in the upper horizon. The total amount of absorbed bases averages 23.4–19.22 m-eq per 100 g of soil, which is slightly less than in the dark gray-brown soils. The main exchangeable cation in the absorbed bases is Ca^{2+}. Among exchangeable cations, calcium predominates, accounting for 78.5–90.7% of the sum of exchangeable bases. The content of exchangeable magnesium is somewhat higher than in dark gray-brown soils; the highest Mg^{2+} values are found in the middle part of the profile in horizons B_1 and B_2. The amount of exchangeable sodium in most profiles is low and ranges from 3.5–6.8–1.92%, only in some profiles in the illuvial horizon does the sodium content reach 11.7–12.5% of the sum of exchangeable bases, indicating signs of solonetzicity in the described soils.

By mechanical composition, the described soils are represented by heavy loamy and clayey varieties. The content of "physical clay" (<0.01 mm) ranges from 45.6 to 69.2%. The distribution of particles <0.01 mm and <0.001 mm in the soil profile shows a gradual increase with depth and indicates high clay content in the middle part of the profile. It is sufficient to note that the content of particles <0.01 mm in horizons B_1 and B_2 reaches 62.7–75.2%. The described soils are mainly formed on the carbonate weathering crust. To characterise dark gray-brown soils, we present a description of a profile laid on the northwestern shaded exposure of the Gobustan massif. Using the relief plasticity method, the soil cover structures of the Gobustan massif were identified and mapped: dendritic type in the foothill area, radial volcanic. It was found that the formation of soil cover structures and the properties of soils are influenced by the northwestern shaded and southeastern sunny parts of slope exposures.

Conclusion

Using the relief plasticity method, the soil cover structures of the Gobustan massif were identified and mapped (scale 1:100,000) – dendritic type in the foothill area, radial-circular, dendritic volcanic in origin. It was found that the formation of soil cover structures and soil properties is influenced by the northwestern shaded and southeastern sunny slope exposures.

It was determined that the diagnostic indicators of mountain gray-brown and mountain light brown soils on the sunny southeastern exposure, compared to soils on the shaded northwestern exposure, include: a decrease in the accumulation-humus horizon (AY = 15–20 cm), humus content (1.0–1.5%), absorbed bases (15–18 mmol-eq), and conversely, an increase in salinity (1.35–2.67%) and pH (8.5–9.0), weakening of granulometric composition (<0.01 mm = 38–45%; <0.001 mm = 35–41%), as well as accelerated erosion processes.

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Plant Nutrient Management for Sustainable Agriculture in Semiarid Climate Conditions

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Abstract

Sustainable agriculture has emerged as a paradigm that integrates ecological health, economic viability, and social equity into agricultural practices. In semiarid climate conditions, where water scarcity and nutrient limitations are prevalent, effective plant nutrient management is crucial for enhancing agricultural productivity while minimizing environmental impact. Implementing tailored management strategies that account for the unique challenges posed by this environment can significantly enhance agricultural productivity and sustainability. Sustainable agricultural practices in semiarid climates involve a combination of crop rotation, cover cropping, efficient water management, and agroforestry systems. Together, these practices have the potential to enhance agricultural resilience against climatic stresses while promoting long-term soil health and productivity. Effective nutrient management strategies must also incorporate an understanding of climatic variability and its implications for soil and crop management. Sustainable agricultural management is a complex interaction of soil health, moisture availability and adaptive agriculture practices.

Keywords: Sustainable agriculture, plant, nutrient, management, semiarid climate.

Introduction

Sustainable agriculture in semiarid climates necessitates a comprehensive approach to plant nutrient management, emphasizing practices that enhance soil fertility while conserving water and other natural resources. The unique challenges presented by these environments, such as low rainfall, nutrient-poor soils, and high evaporation rates, require innovative nutrient management strategies that can sustain agricultural productivity over time. Agriculture in these areas faces multifaceted challenges due to both the degradation of natural resources and the decline in soil fertility (Rathore et al., 2019). Low and erratic rainfall, water scarcity, and inadequate soil moisture not only reduce crop yields but also, at times, lead to complete crop losses (Li et al., 2000). Furthermore, food, fodder, and fuelwood production are severely limited under these conditions. Soil degradation, at the heart of these problems, is one of the main factors threatening food security and directly impacting production capacity, especially in rural areas (Mohamed et al., 2018). In Sub-Saharan Africa and similar semi-arid regions, land degradation, low water productivity, and increasing rainfall variability exacerbate the impacts of climate change (Karanja Ng'ang'a et al., 2016; Woldearega et al., 2018). In this context, the adoption of sustainable agricultural practices is essential not only to increase production but also to conserve resources. Nutrient management for sustainable agriculture in semiarid climates requires a multidisciplinary approach, blending organic amendments, microbiological enhancements, and participatory practices, all rooted in local knowledge and environmental realities to ensure long-term efficacy

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and resilience. In this view the best management practices, and innovative nutrient management strategies that support sustainable agriculture were discussed in semi-arid regions.

Sustainable Agricultural Practices

Sustainable agriculture promotes practices that enhance soil and water stewardship while ensuring high productivity levels. One promising avenue is through Conservation Agriculture (CA), which encompasses minimal soil disturbance, permanent soil cover, and crop rotations. These practices maintain soil health, enhance biodiversity, and improve water retention, vital in semiarid climates where moisture is limited (Devi et al., 2023). The transition to sustainable agricultural practices is particularly beneficial in developing countries, where traditional methods often yield suboptimal results. Studies have shown a significant positive linkage between the adoption of sustainable practices and agricultural production improvements. Such practices not only increase productivity but also contribute to rural economic development (Sikandar et al., 2022).

Crop rotation emerges as a pivotal strategy for improving soil quality and stabilizing yields in semiarid environments. Research indicates that crop rotation can lead to increased soil organic carbon (SOC) and overall water sustainability, as demonstrated in trials on the Loess Plateau, where diverse rotational planting with plastic mulching significantly improved SOC levels while reducing soil degradation normally associated with monocropping practices (Zhang et al., 2023). Particularly, incorporating fallow periods in these rotations allows for moisture retention and supports subsequent crops by providing a 'safety net' of stored soil water, which is crucial given the erratic rainfall patterns typical of semiarid regions (McVay and Khan, 2022). Moreover, the integration of cover crops into crop rotations has been evaluated for its potential to enhance soil fertility and protect against erosion. Cover crops, such as forage varieties, serve dual purposes: they improve soil structure and organic matter content while reducing evapotranspiration losses during the dry season (Baumhardt et al., 2015). A practical illustration of modern sustainable farming practices can be observed in the application of drone-based fertilizer spraying, which enhances precision and reduces resource waste (Figure 1).

Figure 1. Drone with sprinkler sprays fertilizer on green field with crops

Source:https://www.dreamstime.com/agriculture-drone-spraying-corn-field-sunrise-lush-green-fertilizer-pesticide-showcasing-future-farming-image364483109

In regions like the central Great Plains, studies have shown that while cover crops can yield benefits in terms of nutrient retention and soil health, their effectiveness can vary based on local moisture conditions, highlighting the need for tailored management practices (Souza et al., 2019; Thapa et al., 2019). Water management is another critical component of sustainable agriculture in semiarid regions. Techniques such as reduced tillage and conservation tillage have been shown to enhance soil moisture retention and reduce erosion. The implementation of no-till practices not only preserves topsoil but also promotes a more diverse microbiome, leading to improved nutritional availability for crops (Bansal et al., 2014). For example, balanced fertilization combined with no-till in specific crop rotations has been found to significantly increase SOC stocks while promoting higher crop yields (Khorami et al., 2018). Furthermore, agroforestry and silvopastoral systems represent innovative practices that can provide additional benefits in semiarid areas. These systems, which integrate trees with standard agricultural practices, have been shown to improve soil organic carbon sequestration and enhance ecosystem resilience in the face of increasing climate variability (Miller et al., 2015). Such multi-faceted approaches aim not only at maximizing agricultural outputs but also contribute to broader environmental sustainability by mitigating issues such as soil degradation and water scarcity. Cover crops used in field conditions demonstrate the practical application of this approach (Figure 2).

Figure 2. Farm field planted with a cover crop

Source: https://www.stocksy.com/es/photo/87493/farm-field-planted-with-a-cover-crop

The Role of Nutrient Management

Nutrient management plays a critical role in enhancing agricultural productivity under semiarid climate conditions. In such environments, where water and soil fertility are often limited due to high evaporation rates and irregular rainfall patterns, the utilization of effective nutrient management strategies is essential for sustainable agriculture. Precision nutrient management allows farmers to optimize the use of fertilizers, thereby enhancing nutrient use efficiency, particularly in resource-limited environments (Shyam et al., 2021). Researchers emphasize the importance of integrating organic and inorganic fertilizers to improve soil health and crop productivity. For instance, manure combined with chemical fertilizers can lead to substantial gains in rice yield and overall soil quality (Iqbal et al., 2020), demonstrating the benefits of integrated nutrient management systems. In semiarid regions, soil organic carbon and nitrogen are particularly crucial as they serve as vital energy sources for microorganisms, which contribute to nutrient cycling and soil health. Pereira et al. (2021) reported that grazing exclusion significantly enhances soil organic C and N levels in degraded semiarid soils, demonstrating the detrimental impacts of grazing on soil health and nutrient availability. Figure 3 visually demonstrates the liquid manure injection method used in sustainable nutrient management.

Figure 3. Tractor injecting livestock liquid manure with in a field

Source: https://www.gettyimages.in/detail/photo/tractor-injecting-livestock-liquid-manure-with-in-a-royalty-free-image/1502268894?adppopup=true

These best management practices can include proper nutrient application techniques that consider the specific environmental conditions presented in semiarid climates. Furthermore, moisture availability is integral to nutrient dynamics in these regions. Xu et al. (2024) reported that water additions positively influence plant biomass and diversity, which are directly related to nutrient absorption by plants. The accessibility of nutrients like nitrogen is notably influenced by soil moisture levels; inadequate moisture often leads to nutrient loss through volatilization and decreased microbial activity, although specific reference to this point could not be verified (Yadav et al., 2023). Additionally, salinity due to climate changes complicates nutrient availability, as salinity significantly increases the energetic costs for plants, further limiting their growth potential (Asgarian et al., 2021). One effective method for enhancing soil nutrient availability and improving crop yields in semiarid regions is the integration of organic amendments, such as compost and manure. Studies have shown that the application of dairy compost not only enhances soil properties but also increases crop biomass significantly (Acharya et al., 2019). Similarly, the incorporation of animal manure improves soil quality and promotes microbial activity, which is essential for nutrient cycling (Padilha et al., 2020). However, it is critical to manage these organic amendments carefully to avoid nutrient runoff and potential eutrophication in nearby water bodies (Acharya et al., 2019). An example of fertilizer application under field conditions is presented in Figure 4.

Figure 4. Farmer Spreading fertilizer in the Field wheat

Source: https://www.czapp.com/analyst-insights/sustainable-agriculture-how-to-use-fertilizer/

The use of slow-release fertilizers has been suggested as a management practice to mitigate leaching of nutrients, particularly potassium, thereby enhancing efficiency in nutrient uptake by plants (de Oliveira Mendes et al., 2016). Experiments conducted by Montenegro et al. (2020). indicate that mulch cover can significantly reduce runoff and soil loss while improving moisture content, leading to enhanced soil fertility. Furthermore, using biological inoculants and diversifying nutrient sources can improve soil nutrient availability, optimize growth conditions for crops, and minimize reliance on chemical inputs (Meena et al., 2015). The integration of such practices is crucial for fostering agricultural resilience in semiarid areas, as they increase water retention and enhance the soil's nutrient-holding capacity. A visual example of crop rotation implemented to increase plant diversity is presented in Figure 5.

Figure 5. A field with different crops planted in a rotation pattern
Source: https://stock.adobe.com/search/images?k=green+farm+land

Conclusion

Plant nutrient management is integral to achieving sustainable agriculture, especially in semiarid climates characterized by limited resources. Through innovative practices, integrated nutrient management, and a commitment to ecosystem monitoring and assessment, agricultural systems can be transformed into sustainable entities that not only enhance productivity but also preserve environmental integrity. The holistic approach to nutrient management—integrating organic and inorganic resources, promoting biodiversity, and employing conservation practices—will be essential as global food demands continue to rise.

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The impact of inappropriate soil management on soil physical properties

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Abstract

Soil management practices significantly influence soil physical properties, which are critical for supporting plant growth and ensuring sustainable agricultural practices. The management of soil affects not just the physical characteristics such as bulk density, porosity, and water retention but also broader soil health indicators, including organic matter content and microbial activity. Inappropriate soil management practices can significantly degrade soil physical properties, which are crucial for sustaining agricultural productivity and ecological health. Inappropriate soil management practices have a profound negative impact on soil physical properties. The implications of such degradation extend beyond mere agricultural productivity, affecting broader ecological systems and threatening food security. The several researchers reported that inappropriate soil management practices not only lead to soil erosion but also compromise soil structure and fertility, necessitating the adoption of sustainable management strategies.

Keywords: Soil, management, physical properties, quality.

Introduction

The definition of soil management is based on the capacity to improve soil conditions for agricultural use while addressing environmental challenges. Soil management practices are designed to maintain or enhance soil fertility, structure, and biological activity, which are essential for crop productivity and environmental sustainability (Jaworski et al., 2023, Mamatha et al., 2024). The importance of soil management practices extends beyond agricultural productivity; they play a significant role in achieving several United Nations Sustainable Development Goals. Healthy soils contribute to food security, ecosystem health, and water management (Visser et al., 2019, Smith et al., 2021). Soil quality can be understood as the suitability of soil for its specific use, influenced by external factors such as management practices and climate change (Mihelič et al., 2020). This has led to multi-dimensional definitions of soil health, reflecting its role in supporting plant and animal productivity, maintaining water and air quality, and sustaining overall ecosystem functionality (Zhang et al., 2020, Keesstra et al., 2021). Soils are dynamic resources that play an essential role in supporting ecosystems and agricultural productivity. The physical properties of soil, such as bulk density, porosity, and water-retention capacity, are fundamental for its ability to sustain plant growth and maintain environmental quality. However, inappropriate soil management practices can lead to substantial degradation of these properties. In this review, the effects of various poor management strategies such as excessive tillage, inadequate crop rotation and inadequate erosion control on soil properties such as bulk density, porosity and water holding capacity are discussed.

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Overview of Inappropriate Practices

Inappropriate management practices can be explained such as subheading below.

Impact of Excessive Tillage

Tillage is an essential agricultural practice employed to prepare soil for crop production; however, when applied excessively or inadequately. Numerous studies have highlighted the complex relationships between various tillage practices and changes in fundamental soil physical properties that are vital for plant growth and ecological health. Tillage systems can increase soil compaction, alter porosity, and affect water retention and distribution within the soil profile. Similarly, Negev et al. (2020) reported that tillage on wet soils exacerbates compaction and impacts the soil's hydrological properties. Studies indicate that deep tillage practices can lead to the deterioration of soil aggregates, which are crucial for maintaining soil structure and facilitating water infiltration (Xu et al., 2016). Poorly managed soils are prone to structural degradation, resulting in reduced aggregate stability and increased susceptibility to erosion. This degradation can disrupt the soil's ability to retain moisture and nutrients, further exacerbating the challenges faced by plant growth and sustainability in agricultural systems (Usman, 2020). Bulk density measures the mass of soil per unit volume and can be adversely affected by practices such as excessive tillage or compaction from heavy machinery. High bulk density negatively impacts porosity and infiltration rates, restricting root growth and reducing aeration (Baumhardt et al., 2015). Andrade et al. (2010) reported that intensive tillage leads to increased bulk density, adversely affecting crop yields and altering various soil physiological processes. Continuous tillage can lead to soil compaction, resulting in limited root penetration, increased water flow, and reduced microbial activity (Baumhardt et al., 2015).These modifications in physical soil properties can lead to decreased availability of essential nutrients and water for plants (Ghiglieno et al., 2025).

Soil Erosion and Nutrient Loss

Soil erosion is a direct consequence of improper soil management, leading to the removal of nutrient-rich topsoil that is essential for plant health. Soil erosion is a critical environmental concern that significantly influences agricultural productivity, water quality, and land management practices. To address the relationships between soil erosion, soil physical properties, and management practices, it is essential to recognize the multifaceted factors that interplay. The physical disruption caused by erosion alters soil texture and reduces its capacity to store moisture and nutrients (Han et al., 2019). Soil erosion, exacerbated by inappropriate management, further compromises the physical properties of soil. One of the primary physical properties affecting soil erosion is soil texture, which influences water retention and the ease with which soil can be disrupted. Sandy soils, for instance, exhibit higher susceptibility to erosion due to low cohesion and inability to retain moisture compared to clayey soils that have higher aggregated structures (Majoro et al., 2020). Moreover, the bulk density and porosity of soils play crucial roles in erosion dynamics; denser soils generally have reduced erodibility, while less compact soils can be easily disrupted by rainfall and surface runoff (Holz et al., 2015). The impact of soil structure can also not be underestimated; well-structured soils enhance water infiltration and decrease surface runoff, thereby reducing erosion rates (García-Orenes et al., 2012).

Erosion not only removes the fertile topsoil but also diminishes microbial diversity essential for maintaining soil health, leading to a decline in the multifunctionality of the soil ecosystem (Qiu et al., 2021, Paz et al., 2024). This decrease in biodiversity can reduce soil resilience to environmental stresses, making it more vulnerable to further degradation (Tamene et al., 2017, Qiu et al., 2021). Furthermore, the loss of soil organic matter due to unsustainable practices decreases soil aggregate stability, leading to increased vulnerability to erosion (Calabrese et al., 2015, Merlo et al., 2022).

Assessing Soil Compaction and Its Implications

Soil compaction represents a significant threat to sustainable agricultural practices. The cumulative weight of equipment and machinery used in modern farming creates excessive pressure on the soil, leading to alterations in its physical structure. Compaction affects crucial soil properties such as porosity, bulk density, and water retention capacity, which directly influence crop health and productivity (Dauda & Usman, 2019, Augustin et al., 2020, Longepierre et al., 2021). Compacted soils exhibit restricted pore space, which limits water infiltration, root penetration, and gas exchange, ultimately contributing to diminished crop yields (Kim et al., 2010, Pereira et al., 2023). The implications of soil compaction extend beyond immediate agricultural productivity. Increased compaction compromises the soil's biological functions, drastically reducing microbial diversity and activity, which are vital for nutrient cycling (Longepierre et al., 2021; (Stoessel et al., 2018; . These changes can lead to a feedback loop where decreased biological activity further contributes to soil degradation. For instance, heavy machinery can disrupt soil structure, leading not only to mechanical issues but also to reduced resilience in soil ecosystems (Marshall et al., 2016, Longepierre et al., 2021). The interaction of physical, chemical, and biological soil properties means that compromised soil health can lead to broader ecological consequences, such as increased erosion and greenhouse gas emissions from disturbed soils (Stoessel et al., 2018; Ren et al., 2022).

Sustainable Soil Management Practices

One key sustainable practice is the adoption of integrated nutrient management systems, which have been shown to improve soil fertility and overall health. Research indicates that the combination of organic amendments, such as vermicompost and biostimulants, with conventional fertilizers significantly enhances levels of soil organic carbon, nitrogen, phosphorus, and potassium, thereby promoting nutrient availability and improving soil structure (Kumar et al., 2024). Tillage practices also play a critical role in sustainable soil management. Conservation tillage, which includes practices such as no-tillage and reduced tillage, contributes to soil structure preservation, decreased erosion, and improved water retention (Lucas et al., 2010, Zahid et al., 2020). Studies demonstrate that these practices enhance soil aggregate stability and promote beneficial microbial activity, leading to improved nutrient cycling and overall soil fertility (Nandan et al., 2019, Pandao et al., 2023). Excessive tillage can exacerbate soil degradation, thus transitioning to conservation agriculture can be beneficial. By minimizing soil disturbance, farmers can maintain healthier and more resilient soils (Lucas et al., 2010, Dixit et al., 2024). Moreover, the role of cover cropping and crop rotation in sustainable soil management is significant. These practices help to enhance soil biodiversity, increase organic matter content, and improve moisture retention. Crop rotations, including legumes, are particularly advantageous as they can naturally fix nitrogen in the soil, reducing dependence on synthetic fertilizers and enhancing soil fertility over time (Mupangwa et al., 2013; Tahat et al., 2020). This sustainable practice actively contributes to decreasing agrochemical usage, which poses environmental risks through runoff and contamination of water resources (Ukwu, 2024).

Conclusion

As a result, inappropriate soil management practices have a profound negative impact on soil physical properties. Inappropriate soil management significantly degrades soil physical properties, leading to compaction, erosion, and loss of microbial diversity, all of which together undermine soil health and functionality. The physical deterioration of soil resulting from inappropriate management practices is intricately linked to declining soil fertility. Land misuse exacerbates nutrient depletion and organic matter loss, which are vital for maintaining strong soil health and fertility (Fu et al., 2000). The implications of such degradation extend beyond mere agricultural productivity, affecting broader ecological systems and threatening food security. It is essential that sustainable soil management strategies be adopted to mitigate these adverse effects, preserve soil health, and ensure long-term agricultural viability.

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Prospects for the Use of Soil Resources in the East Zangezur Economic Region of Azerbaijan in Agriculture

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Abstract

The newly established East Zangezur Economic Region (comprising the Zangilan, Gubadli, Jabrayil, Lachin, and Kalbajar administrative districts), as a major agricultural region playing an important role in Azerbaijan's economy, has favorable soil and climatic conditions, creating vast opportunities for the development of crop production and livestock farming. The total area of the East Zangezur Economic Region is 744.8 thousand hectares. The research involved ecological, botanical, mathematical-statistical, visual-observational, cartographic, and laboratory methods. A soil map of the East Zangezur Economic Region at a scale of 1:100,000 was compiled, providing a classification of 14 subtypes and 50 soil varieties included in the soil fund. According to the research data, the predominant soils in the economic region are mountain-meadow soils (30.90%), followed by mountain-brown soils (23.64%). An assessment of the agricultural soils in the economic region based on their designated purpose has been conducted, revealing that the lands are most suitable for pastures and hayfields (69.03%) as well as arable land (19.51%). Administratively, the largest share of cultivated agricultural crops (34.57%) and perennial plantations (65.45%) is concentrated in the Jabrayil district, while the majority of pastures are located in the Kalbajar district (36.42%). The prospects for agricultural development in the East Zangezur Economic Region have been studied, and the structural indicators of the projected land areas have been analyzed. It has been deemed appropriate to allocate the largest areas for grain crops in the Jabrayil (10.4 thousand ha) and Gubadli (6.3 thousand ha) districts, for fruit and berry orchards in the Gubadli (2.5 thousand ha) and Zangilan (2.2 thousand ha) districts, for vineyards in the Jabrayil district (1.2 thousand ha), and for tobacco, potatoes, and vegetables in the Gubadli district (400 ha). According to livestock development forecasts for the economic region, the Lachin and Kalbajar districts have the greatest potential for this sector.

Keywords: East Zangezur, agriculture, soil map, pastures, arable lands, perennial plantations.

Introduction

Humanity is facing unprecedented challenges in agriculture: the climate is changing, the global population is growing rapidly, cities are expanding, diets are changing dramatically, and soils are becoming increasingly degraded. In this rapidly changing world, given the urgent need to end hunger and ensure food security and nutrition, understanding and achieving sustainable soil management has never been more important. Indeed, the Sustainable Development Goals define the need to restore degraded soils and improve soil health. In this

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regard, scientists from different countries are conducting diverse research aimed at achieving sustainable development of regions based on the efficient use of soil resources.

To assess the natural resource potential of agricultural areas, the authors used indicators of heat supply, moisture availability, and soil fertility. Agroclimatic conditions were characterized based on long-term average data on the sum of air temperatures above +10°C and the annual amount of precipitation, while the evaluation of soil properties was conducted on the predominant types of arable land (Aksenova and Schmidt, 2024).

When studying the agricultural potential of land in various regions, the integration of the Analytic Hierarchy Process (AHP) and Geographic Information System (GIS) is used to determine land suitability for cultivating major agricultural crops with the goal of establishing a sustainable agro-system. Additionally, models such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and the Multi-Criteria Optimization and Compromise Solution (VIKOR) are applied (Kalaiselvi et al. 2024; Pujiono et al. 2024; Shaw et al. 2025; Saha and Gayen, 2025).

The assessment of soil resources suitable for cultivating agricultural crops (such as barley, wheat, and others) includes a quantitative evaluation of land and its classification based on Land Mapping Units (LMU), as well as the creation of land suitability maps. In their evaluation of land suitability, Abate and Anteneh (2024) used data on climatic conditions, topography, and the physicochemical properties of soil, analyzed with the help of the ArcGIS Environment and the Priority Estimation Tool (PriEsT).

Upreti et al. (2024) examined trends in the use of fertile land for non-agricultural purposes, especially along the rural–urban interface and on urban outskirts, which poses a significant threat to food security in developing countries.

According to the findings of Danilov-Danilyan and Klyuev (2023), in some regions the use of renewable resources (biological, forest, soil, agroclimatic, and water), as well as non-metallic construction materials, is increasingly concentrated in compact areas near central settlements and major transportation routes, focusing on the exploitation of the “best lands.” As a result, the more successfully regional agriculture develops, the greater the resource-ecological imbalance.

Land use and land cover change (LULCC) serves as an important indicator of human land use patterns in different regions and plays a key role in conserving natural resources. Major drivers of LULCC include agricultural expansion, policy changes, population growth, land scarcity, and biophysical factors. The consequences of such changes include biodiversity loss, depletion of forest resources, habitat alteration, reduced water quality and availability, and declining crop yields. Therefore, studying global land use patterns becomes a priority for addressing climate change challenges and promoting sustainable development (Mir et al. 2025). Kılıç et al. (2024) assessed land suitability for sustainable agriculture (SALSA) for wheat and perennial crops, using factors affecting yield and indicating land degradation.

The integration of the liberated territories of Azerbaijan into the country’s economy and economic circulation required an update to the economic zoning system, as well as a more accurate and efficient distribution of productive forces and resources. To support the development of the liberated territories and their integration into the national economy, as well as to enhance planning efficiency in other economic regions, on July 7, 2021, the President of the Republic of Azerbaijan signed a Decree on the new economic zoning of Azerbaijan (“On the New Economic Zoning of Azerbaijan,” 2021). According to this Decree, a new zoning system was introduced, and 14 economic regions were designated.

Each economic region has its own areas of specialization and unique characteristics. Various factors play a significant role in this process, including geographical, natural, and economic conditions (Aliyev, 2021). Other important factors include employment patterns, customs and traditions, and the national composition of the population. Effective and systematic management of economic regions is essential, along with the planning and implementation of priority projects, the development and application of state financial and investment mechanisms, and the creation of favorable conditions for the development of alternative sources of funding. Furthermore, ensuring employment and stimulating economic activity, developing social infrastructure, providing production and trade infrastructure, encouraging entrepreneurship, and creating a favorable business environment are key elements of regional development (Aliyev et al. 2022).

Material and Methods

The total area of the East Zangezur Economic Region is 744.8 thousand hectares (Figure 1). The research involved ecological, botanical, mathematical-statistical, visual observation, cartographic, and laboratory methods of investigation.

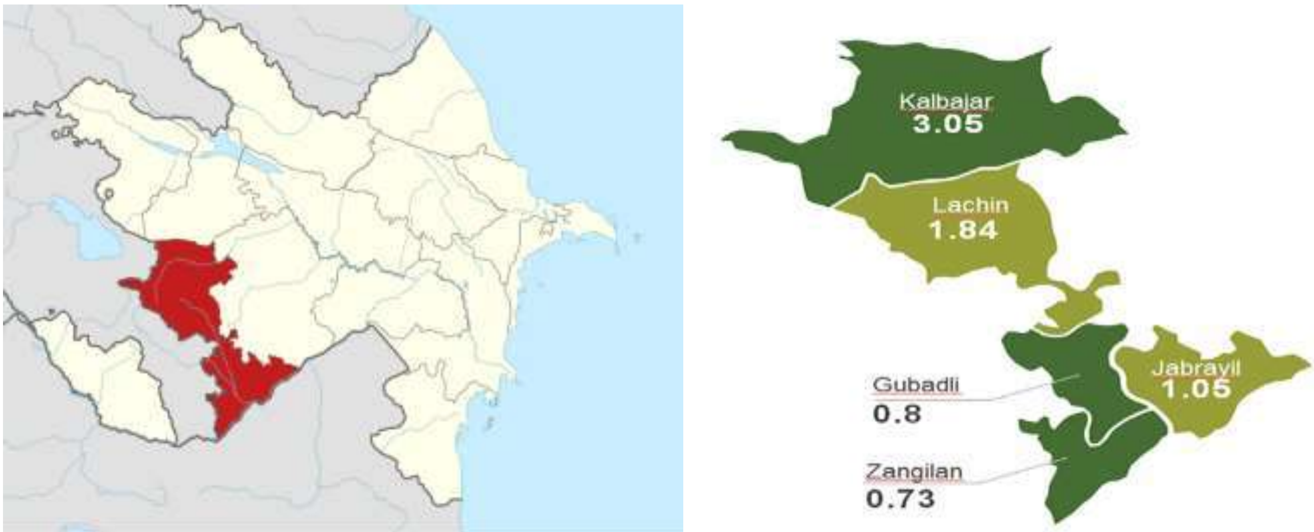

Figure 1. Map of the a) location of the study area and b) distribution by administrative districts

To create a Digital Elevation Model (DEM) of the East Zangezur Economic Region, high-resolution elevation data were obtained from publicly available sources such as the Shuttle Radar Topography Mission (SRTM) and the Global Digital Elevation Model (GDEM) from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Weibel and Heller, 1991; USGS, 2019). In addition, satellite imagery and topographic maps were included to improve the accuracy of the dataset. To ensure the accuracy of the DEM, validation was conducted using existing ground measurement data and cross-referencing with available topographic maps. The final map was then exported in high-resolution formats for integration into reports and GIS applications.

The soil map of the East Zangezur Economic Region was created based on the Soil Map of Azerbaijan, with additional spatial data used to ensure accuracy and completeness. The region's soil cover was vectorized using ArcGIS, allowing for the transformation of raster data into vector format for more precise spatial analysis (McGee et al. 2005). The digitized data were adjusted to determine the exact boundaries of various soil types.

Results and Discussion

Relief, Geology and Geomorphology

The East Zangezur economic region includes the Zangilan, Gubadli, Jabrayil, Lachin and Kalbajar regions. It is located along the border with Armenia, in the eastern part of the Zangezur plateau, surrounded by the Zangezur range, and extends over a vast territory from Lachin and Kalbajar to Nakhchivan.

The Karabakh Volcanic Plateau — encompassing the Kalbajar and Lachin districts of the East Zangazur Economic Region — is situated upstream along the Tartarchay and Hakari rivers. We have developed a digital territorial model map of the economic region (Figure 2). According to the map, the terrain extends in a broad zone from northwest to southeast, with elevations ranging from 3,681 m down to 160 m. The foundation of the Karabakh Volcanic Plateau is composed of ancient rock formations.

Large longitudinal faults run along the north-eastern and south-western edges of the plateau, along the central line of this area there are numerous Pliocene and Pleistocene volcanoes, thermal and cold mineral waters. Most of the plateau is in the highland zone. The main features of the plateau are its formation as a result of Upper Pliocene-Quaternary volcanism, and the relief details are the result of modern nival-denudation and ancient glacial processes. The watershed of the plateau is located at an altitude of 3000-3500 m, the relief is quite flat and wavy.

The inclined accumulative plain of Hakari is composed of alluvial and partly alluvial-proluvial deposits of the late Pliocene age. The lava layers form a high-mountain plateau with steep and small (150-100 m and less) slopes. The plateau narrows to the deep valleys of the Tartarchay, Bargushad and Yildrymsuchay rivers. The main composition of the surface of all plateaus was formed as a result of the eruption of Pleistocene lavas. The watershed of the plateau is characterized by high-mountain relief. The plateau is rich in minerals, building materials, gold (Zod Pass) and mineral springs (Istisu, Minkend, etc.).

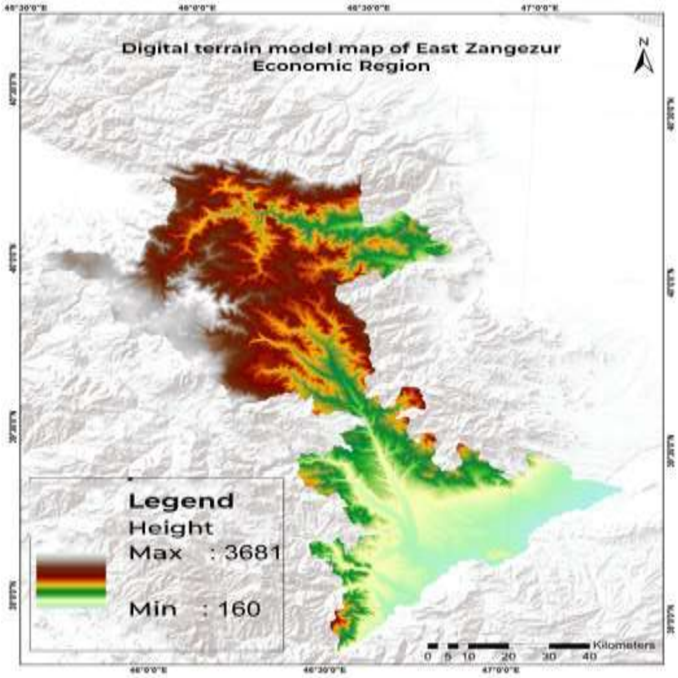

Figure 2. Digital Terrain Model Map of the East Zangezur Economic Region

The southern part of the study area belongs to the lower reaches of the Okchuchay and Hakari rivers, rises to an altitude of 2500 m in the northwestern part of the Lower Araz Plain and consists of volcanic and volcanic-sedimentary rocks of the Jurassic, Cretaceous, Paleogene, Neogene and Quaternary periods (https://ereforms.gov.az/files/review/pdf/az/50106b9302c648fb32645cc9493f2dad.pdf).

In the upper reaches of the Hakari River and on the southern slopes of the Mikhtoken ridge, there are watersheds with very different structures. The river valleys are characterized by relatively gentle slopes.

Climate

The mountain system of the Lesser Caucasus is distinguished by a variety of climatic conditions and, in turn, has a significant impact on the climate of the lowland regions of the republic. Areas of the Lesser Caucasus at elevations up to 300–400 meters experience hot summers and mild winters. The average temperature in the warmest months (July and August) ranges from 24–26 °C, with maximum temperatures reaching 35–37 °C. The average temperature in the coldest month (January) is between 1.0° and 3.9 °C, while the absolute minimum drops to −15 to −25 °C. In the foothills of the Lesser Caucasus, the first frosts occur in the third decade of November, and the last ones — in mid-March.

The low- and mid-mountain regions of the Lesser Caucasus in Azerbaijan are characterized by a mild climate. The sum of active temperatures here is 3,000–3,500 °C. The average temperature of the warmest months ranges from 12–10 °C, while the maximum temperature varies between 35–38 °C (Abdurakhmanov, 2023a). The average temperature of the coldest month is 1–2 °C, and the absolute minimum temperature drops to −27 to −28 °C. The frost-free period lasts 200–230 days, and frost days occur from mid-November to the second half of April. Annual precipitation ranges from 300 to 800 mm. In warm months, heavy rains frequently occur, sometimes accompanied by hail. A stable snow cover does not form every year, and snow typically melts soon after falling. In severe winters, the snow cover can persist for 30–40 days. Winds are infrequent and generally light to moderate, with an average annual speed of 1.5–3.0 m/s.

The region has strong potential for the development of various agricultural sectors, primarily grain farming, viticulture, potato cultivation, tobacco growing, and fruit growing, as well as, to some extent, sericulture and livestock farming. The climatic conditions allow agricultural crops to be grown here under ideal conditions.

Hydrography

The largest river flowing through the northern part of the study area is the Tartarchay. Its main tributaries include the Tuthun, Lev, Zaylik, Keshtek (Alolar River), and Karaagach (Sarkar River). The Nargiz, Umudlu, Chechevitsa, Maral, and several smaller rivers flow directly into the Tartar River. The Khachinchay River originates in the Oyukhlu and Yildirim mountains, located to the east of the Tuthun River, and flows toward Aghdaban.

The rivers in the southern part of the study area include the Araz, Okhchuchay, Hakari, and Basitchay. These rivers are fed by snowmelt, groundwater, and partially by rainfall (Mustafabeyli, 2021). Water levels in these rivers rise during the warmer months. The source of the Hakari River—the largest river in the region—is at an elevation of 2,600 meters. The river valley splits into four branches, consisting of several narrowing and widening segments. The depth of the tributaries (Shelve, Gorchu, etc.) is relatively shallow in the upper reaches and gradually increases downstream.

The river network in the southwestern part of the study area belongs to the Araz River system, while part of the southeastern region falls within the Kura River basin. River network density varies from 0.2 km/km^2 to 1 km/km^2, depending on absolute elevation and lava fragmentation. Floods occur during intense snowmelt in spring and early summer. In late summer, water levels drop, and the rivers are mainly sustained by groundwater. Reservoirs located within the economic region include the Greater and Lesser Alagol, Zalhagol, and Sarsang.

Vegetation Cover

The main vegetation cover of the economic region consists of alpine and subalpine meadows and forests. The forested area with rare tree species amounts to 92 thousand hectares (9% of the country's forests), 72% of which are mountainous forests of tourist and recreational significance, located in the administrative districts of Kalbajar and Lachin. The vegetation in the northern part of the studied region is represented by shrub and sparse forest meadows, broad-leaved mountain forests (oak, alder, beech), as well as subalpine and alpine meadows. The total forest resources of the East Zangezur Economic Region amount to 178.1 thousand hectares, and their distribution by administrative districts is shown in Figure 3.

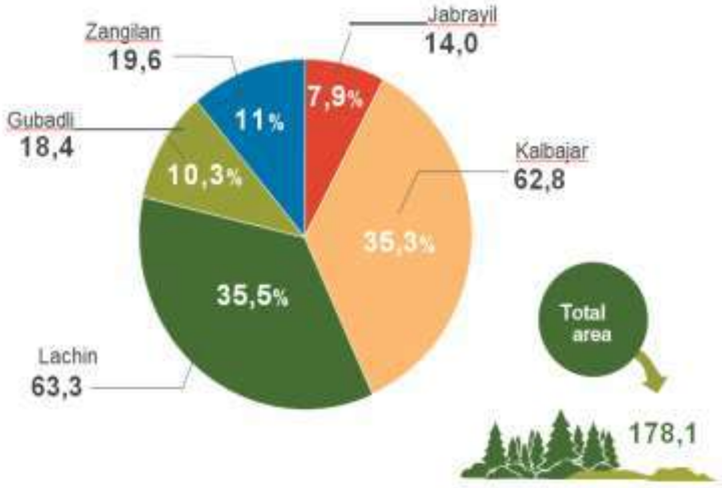

Figure 3. Forest resources of the East Zangezur Economic Region

As seen from the diagram, the largest share of forest resources is concentrated in the Lachin (35.5%) and Kalbajar (35.3%) districts, while the smallest is in the Jabrayil district (7.9%) (Abdurrahmanov, 2023b).

In the Aras Plain, located in the southern part of the region, steppe landscapes and shrubs growing on light chestnut soils have developed due to the arid climate ((Ibadullayeva et al. 2023). These areas are used as winter pastures. Juniper thickets are found along the Hekarichay River. In the Basitchay Reserve, eastern plane trees have been naturally preserved.

Soil Resources

The soil cover of the East Zangezur Economic Region has developed under the influence of diverse climatic, geomorphological, and hydrogeological conditions, shaped by the high mountains of the Lesser Caucasus mountain system, which gradually descend eastward and transition into the Kura-Aras lowland. In this area, mountain-meadow soils are common in the alpine meadows of the highlands; brown mountain-forest and cinnamon mountain-forest soils are found in forested areas; mountain chernozem and mountain chestnut soils prevail in the mid-mountain and low-mountain zones; and in the foothills and lowlands, gray-brown, gray, gray-meadow, and alluvial-meadow soils are predominant (Mammadov et al. 2024). Aside from forest-covered lands, the remaining areas are widely used for agriculture, taking into account their qualitative characteristics.

To study the current state of the soil cover in the Jabrayil, Kalbajar, Lachin, Gubadli, and Zangilan districts, which are part of the East Zangezur Economic Region, an analysis was conducted using archival and cartographic materials stored in the Soil Science and Agrochemistry Institute of the Azerbaijan Republic's National Academy of Sciences (Soil Map of Azerbaijan, 1996). In addition, soil field research was carried out. Based on the obtained materials, we prepared the “Soil Map of the East Zangezur Economic Region” at a scale of 1:100,000 (map) (Figure 4).

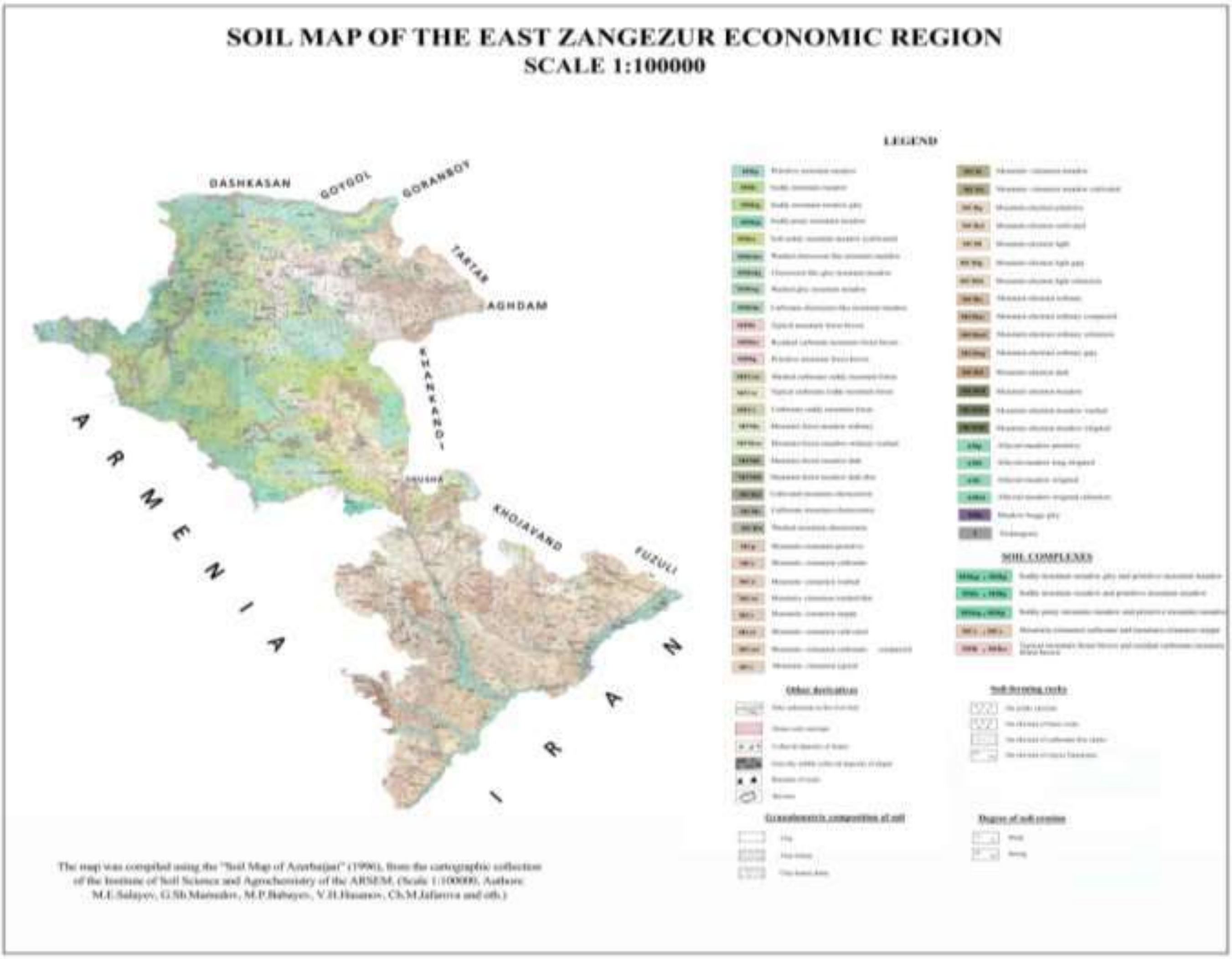

Figure 4. Soil Map of the East Zangezur Economic Region

Based on the soil map of the economic region, the areas of soil types and subtypes in the studied region were calculated. The diagram below reflects the distribution of resources by soil types and subtypes (Figure 5).

The total area of the economic region is 744.8 thousand hectares. As seen on the map, the soils of the East Zangezur Economic Region are grouped into 14 types and subtypes and are unevenly distributed across the territory. According to our research, the predominant soils of the East Zangezur Economic Region are mountain-meadow soils, occupying an area of 230,171 hectares or 30.90% of the total area. In the studied territory, the following subtypes of mountain-meadow soils are found: primitive, meadow, meadow-peaty, chernozem, and mountain-meadow-steppe.

In second place in terms of distribution are mountain cinnamon soils, with five subtypes found in the region: underdeveloped, carbonate, typical, washed, and cultivated mountain brown soils. Among them, the mountain cinnamon steppe soils predominate, covering 52,210 hectares, followed by washed soils, which cover 33,870 hectares.

The total area of mountain-forest-meadow soils, which are common in the high mountainous zone, amounts to 24,895 hectares, or only 3.44% of the area.

Three subtypes of brown mountain-forest soils are distinguished in the studied territory (typical, residual-carbonate, and primitive), of which the typical brown mountain-forest soils prevail, occupying 23,520 hectares, or 3.16% of the area.

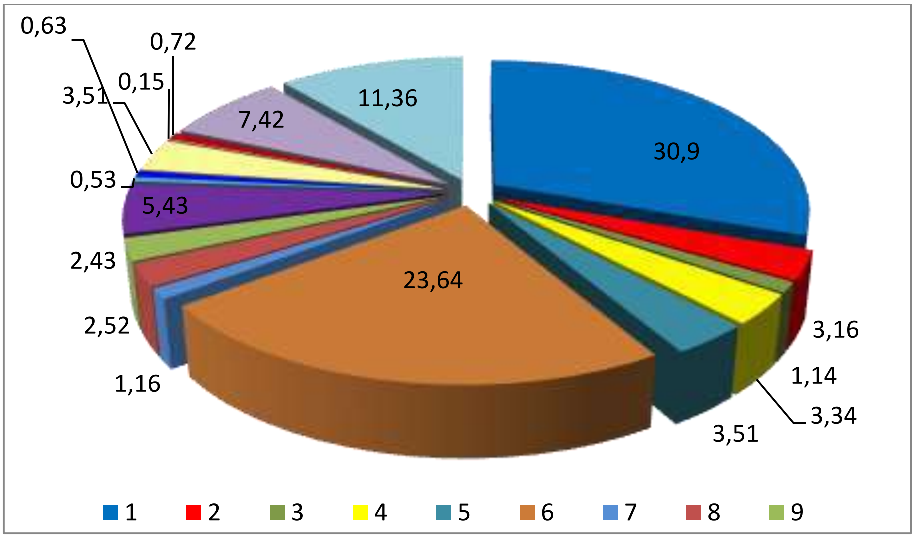

Figure 5. Soil cover of the East Zangezur Economic Region: 1-mountain-meadow; 2-mountain-forest brown; 3-carbonate soddy mountain-forest; 4- mountain-forest meadow; 5-mountain-chernozemic; 6-mountain-cinnamon; 7-mountain-cinnamon meadow; 8- mountain chestnut cultivated ; 9- mountain chestnut light; 10- mountain chestnut ordinary; 11-mountain chestnut dark; 12-mountain chestnut-meadow; 13-alluvial-meadow; 14-meadow-boggy gley; 15-technogenic soils; 16 - soil complexes; 17 - other soils.

Mountain chestnut soils are found in the East Zangezur Economic Region over an area of 40,456 hectares (5.43%) and are divided into four subtypes: dark, ordinary, compacted and solonetzic. Based on research, it was determined that among the mountain chestnut soils, the ordinary mountain chestnut subtype is the most widespread, occupying 21,115 hectares.

Among other soil types, mountain chestnut-meadow soils cover 0.63% (4,666 hectares) of the studied area, while alluvial-meadow soils account for 3.51% (26,145 hectares) of the total area.

Technogenic soils, unsuitable for agricultural use, are spread across 5,395 hectares (0.72%), and soil complexes cover an area of 55,275 hectares (7.42%).

Use of Soil Resources in Agriculture

It is known that out of the 1,670.3 thousand hectares of territory in Azerbaijan liberated from occupation, 680.8 thousand hectares are agricultural lands, more than 10.7 thousand hectares are household plots (which are also suitable for agricultural use), and 247.3 thousand hectares are forested areas (Valiyev, 2020).

The East Zangezur Economic Region is a major agricultural area that plays an important role in Azerbaijan's economy. Favorable soil and climatic conditions provide broad opportunities for the development of both crop production and animal husbandry.

Before the occupation, various agricultural sectors were well-developed here, including: grain cultivation, viticulture, tobacco growing, forage production, potato farming, vegetable growing, cotton growing, and livestock farming (Shirinzade and Aliyev, 2023).

By the end of the 20th century, this economic region accounted for: 14.3% of the grain, 31.5% of the grapes, 14.5% of the meat, 17.1% of the milk, 19.3% of the wool, and 17.0% of the silkworm cocoons produced in the country (Nadirov and Mammadova, 2023). It should be noted that viticulture and tobacco cultivation in these districts have a very ancient history(https://agroeconomics.az/az/article/34/isgaldan-azad-olunan-erazilerimizde-kendteserrufa/).

We conducted an analysis of fund materials and created diagrams that illustrate the level of land use for agricultural purposes in the Eastern Zangezur economic region by each individual district (Figure 7).

According to Diagram 6, the main portion of agricultural land in the Jabrayil district—23.2 thousand hectares (44.1%)—is used as pastures, and 20.5 thousand hectares (39.0%) are under cultivation (https://www.stat.gov.az/source/region).

The largest areas of summer pastures are found in the Kalbajar (76.4 thousand hectares) and Lachin (69.3 thousand hectares) districts. The largest area of winter pastures is in the Zangilan district (23.3 thousand hectares), while the largest areas of perennial plantings (7.2 thousand hectares) and croplands (20.5 thousand hectares) are located in the Jabrayil district.

The second-largest area of arable land is in the Gubadli district (15 thousand hectares), and the second-largest area of land under perennial plantings is in the Zangilan district (2.7 thousand hectares).

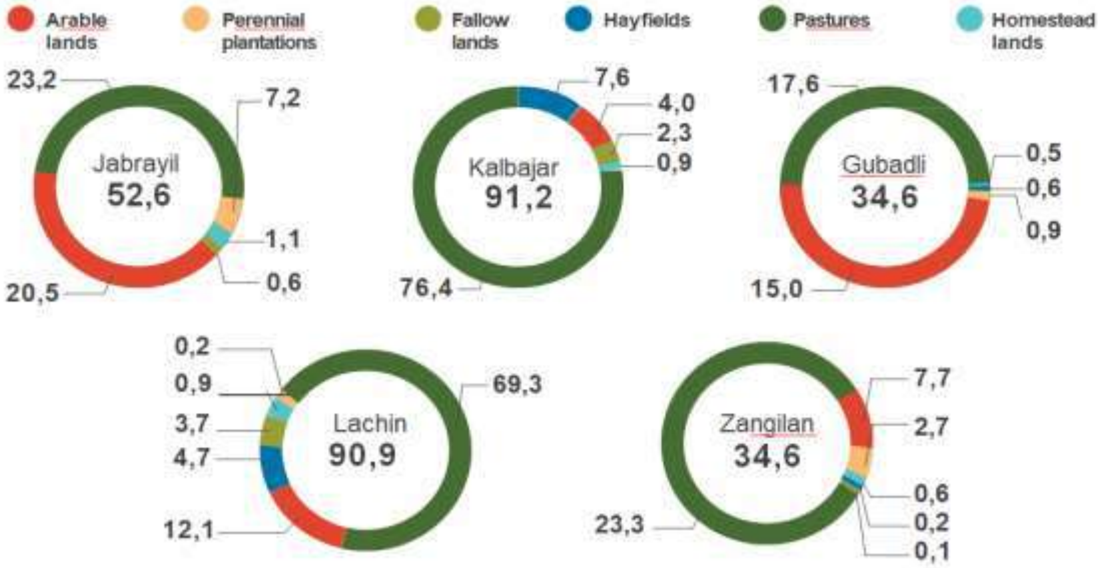

Figure 6. Level of Land Use for Agricultural Purposes in the East Zangezur Economic Region

Specialists from the Ministry of Agriculture of the Republic of Azerbaijan have developed agricultural development forecasts for the liberated territories (https://agrodata.az/). Diagram 7 presents the forecasted structural indicators of arable land in the East Zangezur Economic Region, based on data provided by experts from the Agrarian Research Center of the Ministry of Agriculture (Figure 6).

According to the forecasts:

- The largest volumes of grain cultivation are expected in the Jabrayil (10.4 thousand ha) and Gubadli (6.3 thousand ha) districts.
- The largest areas of fruit and berry orchards are projected in the Gubadli (2.5 thousand ha) and Zangilan (2.2 thousand ha) districts.
- The largest vineyard areas will be planted in the Jabrayil (1.2 thousand ha), Gubadli (1.0 thousand ha), and Zangilan (1.0 thousand ha) districts.
- The largest areas for tobacco cultivation are forecasted in Gubadli (400 ha) and Zangilan (300 ha).
- The largest areas for potato and vegetable cultivation will be in Gubadli (400 ha) and in Zangilan and Jabrayil (300 ha each).

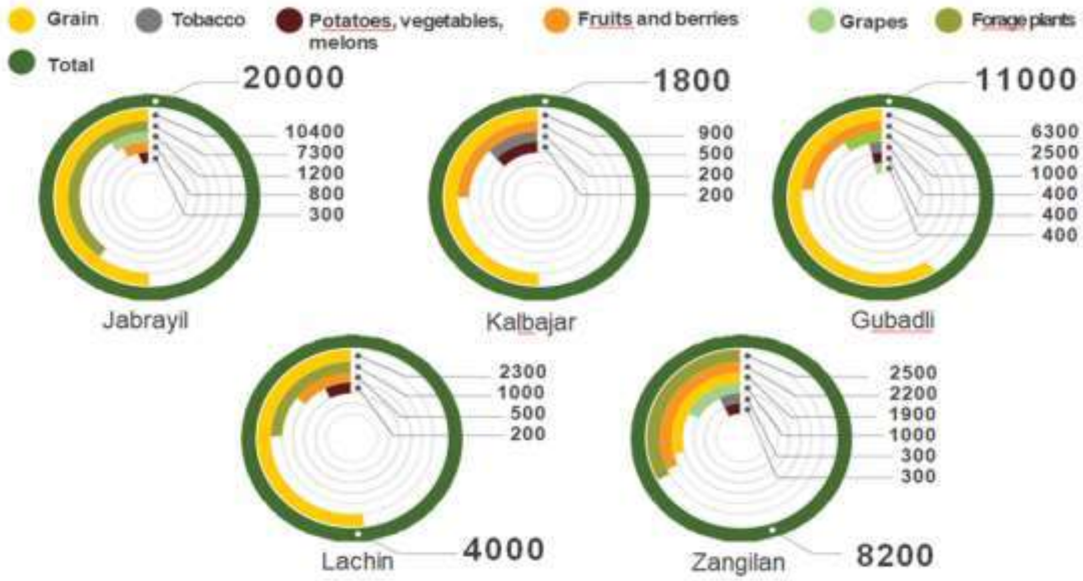

Figure 7. Projected Structure of Arable Lands in the East Zangezur Economic Region

In conclusion, it can be noted that the territory of the East Zangezur Economic Region, defined based on the new administrative division, possesses significant natural, soil, and economic resources, as well as great potential for the development of various economic sectors, including industry, tourism, agriculture, and particularly the agrarian sector—with a focus on crop production and livestock farming. These resources will be directed toward the development of the economic region, further strengthening the power and influence of our country in the Karabakh region.

Conclusion

Based on the analysis of archival and cartographic materials, as well as soil field and laboratory research, an assessment of the current natural and ecological conditions of the Eastern Zangezur economic region was conducted. A "Soil Map of the East Zangezur Economic Region" (scale 1:100,000) and a digital relief model (based on GIS technologies) were developed. The distribution of soil resources was identified by soil types, subtypes, and species diversity across the studied area.

The soil resources of the East Zangezur Economic Region were evaluated in terms of their suitability for agriculture. The level of land use for agricultural purposes was determined by administrative districts. It was found that the largest area of summer pastures is located in the Kalbajar district (76.4 thousand ha), while the largest areas of perennial plantings (7.2 thousand ha) and grain crops (20.5 thousand ha) are found in the Jabrayil district. In total, 209.8 thousand hectares (69.03%) of the region's agricultural lands are primarily used as pastures and grazing areas.

The agricultural development prospects of the East Zangezur Economic Region were also reviewed. Structural indicators of the forecasted arable land area were analyzed. The largest projected areas for grain cultivation are in the Jabrayil (10.4 thousand ha) and Gubadli (6.3 thousand ha) districts. The largest fruit and berry orchards are planned in Gubadli (2.5 thousand ha) and Zangilan (2.2 thousand ha), the largest vineyards in Jabrayil (1.2 thousand ha), and the largest tobacco, potato, and vegetable cultivation areas in Gubadli (400 ha).

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Heavy metal content in soils of the dried bottom of the Aral Sea

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Abstract

After the drying up of the Aral Sea, lands with a very large area were formed, only on the territory of Uzbekistan there is an area greater than 5 million hectares. The study of the content of heavy metals in these soils is very important in the ecological and agronomic assessment of the soil of the dried bottom of the Aral Sea. Selected soil samples from the southern and eastern parts of the dried bottom of the Aral Sea were subjected to chemical analysis for the content of heavy metals by the method of atomic emission spectrometry. The gross content of heavy metals was determined. The results of the analyses show that the soils of the dried bottom of the Aral Sea contain large amounts of arsenic, copper, and molybdenum, the amount of which exceeds their maximum accessible concentration and background content. The gross content of chromium and cadmium in most cases was at the levels of their background amount. The content of other heavy metals was significantly lower than their background amount, which is safe for these soils and the environment. But it should be taken into account that the heavy metals of the dried bottom of the Aral Sea probably consist of compounds of simple salts that are highly soluble in water, i.e., have high availability for plants and microorganisms.

Keywords: Clark, gross content, heavy metals, maximum permissible concentration, pollution, soil.

Introduction

Heavy metals are a major pollutant of the environment and living organisms (Zaynab et al., 2022; Lian et al., 2019). With a high content of heavy metals in the soil, its ecological state deteriorates, and important soil processes are disrupted (Abdu et al., 2017; Li et al., 2019). At the same time, heavy metals have a negative effect on plant nutrition, for example, on the absorption of certain important nutrients, on the growth, development and accumulation of plant yields (Khan, 2015; Aboyeji, 2020; Hussain et al., 2023). With a high content of heavy metals in the soil, the quality of agricultural crops decreases, and in many cases, becomes unsuitable for use (Wang et al., 2015; Zwolak et al., 2019). Heavy metals have a negative effect on the number of bacteria and fungi, change the species composition of the fungal community and disrupt the ecological processes of transformation of soil organic matter (Baldrian P., 2010). Saprotrophic fungi are especially sensitive to heavy metals, since they mainly use extracellular enzymes in nutrition, which are primarily affected by heavy metals. In general, microorganisms are much more sensitive to heavy metals than soil animals and plants (Inobeme, 2021; Giller et al., 1998). Therefore, the study of the soil microbial community

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can well reflect the degree of soil pollution with heavy metals and its impact on the ecological state of the soil (Chu, 2018).

Metals will migrate rapidly when released into the soil, then their distribution will be slow (Lu et al., 2005). The diffusion of heavy metals in the soil decreased in the following order: Pb>Cu>Zn>Cd.

Heavy metals accumulate in living organisms and have a detrimental effect on their life. Even at low levels in the soil, heavy metals become hazardous as they accumulate in living organisms and in the soil. Heavy metals in the soil do not decompose or turn into safe substances (Rahman and Singh, 2019; Brodin et al., 2017; Ferrey et al., 2018; Inobeme, 2021). By studying the microbial community, the degree of soil pollution by heavy metals can be determined (Chu, 2017).

Heavy metals are dangerous for living organisms and the environment, especially in mobile forms. The mobility of heavy metals depends on many soil properties and conditions. In carbonate soils, the mobility of heavy metals such as iron, manganese, copper, and zinc decrease and becomes immobile and insoluble. The mobility of heavy metals in the soil is affected by the reaction of the environment (pH), the conditions of the oxidation-reduction reaction, aeration, soil particle size distribution, and the presence and concentration of individual ions (Caporale and Violante, 2016). The efficiency of their removal from the soil horizon depends on the mobility of heavy metals and their adsorption capacity (Kim et al., 2001).

As the concentration of heavy metals in the soil increases, enzyme activity decreases. There is a close inverse correlation between the degree of soil pollution with heavy metals and the enzyme activity in the soil (Mikanova, 2010; Chu, 2017). However, heavy metals have different effects on different enzymes. Heavy metals have the least negative effect on enzymes involved in the carbon cycle in the soil, but they have a strong effect on enzymes involved in the nitrogen, phosphorus and sulfur cycles. For example, the activity of arylsulfatase and phosphatase was strongly inhibited by heavy metals (Kandeler et al., 1996). Heavy metals not only reduce the number and activity of microorganisms in the soil, but also their diversity (Abdu et al., 2017; Inobeme, 2021). At the same time, the biomass of microorganisms decreases and the population is weakened.

The toxicity of some polyvalent heavy metals depends on their oxidation state and, therefore, on the oxidation-reduction conditions in the soil. Thus, arsenite (As^{3+}) is more toxic and bioavailable than arsenate (As^{5+}). Therefore, with increased conditions for reduction processes in the soil, the toxicity of arsenic increases. Increased oxidation processes in the soil reduce the toxicity and bioavailability of arsenic. The toxicity of chromium changes in the opposite direction. Since chromates (Cr^{6+}), a more oxidized form of chromium, is toxic than the Cr^{3+} cation. Chromium in the form of the Cr^{3+} ion is non-toxic to plants and is an essential nutritional element for animals. At the same time, Cr^{6+} is mobile in the soil and is easily accessible to organisms. Therefore, with increased oxidation processes in the soil, the toxicity of chromium increases. Selenium is also highly toxic at high concentrations. However, selenite (Se^{4+}) is more toxic than the more oxidized form of selenium, selenate (Se^{6+}). Therefore, reducing conditions in the soil increase the toxicity of selenium (Caporale and Violante, 2016).

Even when the concentration of heavy metals is below the standard values, they can accumulate in certain soil horizons, and over time, due to the redistribution of heavy metal ions in certain horizons, their content will increase significantly. This creates conditions for soil pollution with heavy metals. In the experiment conducted in China, heavy metals such as Zn, Pb, Cd, Hg, Cu accumulated in the 0-20 cm layer, Zn, Cu, Cd, Hg - in the 20-40 cm layer compared to the background. At the same time, 80.2% of heavy metal concentrations in the soil were formed due to anthropogenic factors. At the same time, Cd and Hg had the highest mobility (1.16 - 46.8% of their total content), which makes them hazardous to the environment (Sun et al., 2019). And at the same time, heavy metals accumulated due to anthropogenic factors can be very mobile and more dangerous than their natural sources (Bolan et al., 2014).

On the territory of Uzbekistan, as a result of the drying up of the Aral Sea, a large area of land was formed, which is about 5 million hectares. In these soils, a lot of water-soluble salts have accumulated, among which there are a lot of toxic salts and heavy metals. This leads to many problems for the environment. Therefore, the study of the content and distribution of heavy metals in the soils of the dried bottom of the Aral Sea is relevant.

Material and Methods

To study the content of gross forms of heavy metals, soil samples were taken from the southern part of the dried bed of the Aral Sea - near the city of Muynak from the zero point (0-headquarters), helicopter pad, 22 km, and from the eastern part - in the Koktash area (coordinates $43040^{I}52^{II}$ and $60002^{I}54^{II}$). The content of heavy metals was determined on an atomic emission spectrometer with inductively coupled plasma (ICPE-9820 Shimadzu).

Results and Discussion

The results of the study show that the soils of the dried bed of the Aral Sea contain heavy metals in large quantities. Of the most dangerous heavy metals, cadmium is contained in the soil of the dried bed of the Aral Sea in the southern part in the 0-stab 0.031 ppm, at 22 km - 0.129 ppm, on the helicopter pad - 0.049 ppm, in the eastern part - in the 0-10 cm soil horizon 0.118 ppm, in the 10-30 cm horizon - 0.042 ppm, in 30-50 cm - 0.111 ppm (Table). The highest content of gross cadmium forms was observed in 22 km of the southern part of the dried bed of the Aral Sea and in the upper 0-10 cm horizon of the dried bed of the eastern part of the Aral Sea. The maximum permissible concentration of gross cadmium in the soil is 2 ppm, which shows the low concentration of cadmium in the soils of the dried bed of the Aral Sea. But it is necessary to take into account the content of cadmium in these soils in the form of mineral salts, which shows their high mobility. It is transferred with soil particles by wind and can pollute irrigated soils. The content of cadmium was significantly lower than its Clarke content in the soil and the earth's crust. Another dangerous heavy metal is arsenic. The highest content of arsenic was noted in the southern part of the Aral Sea - 126-184 ppm, and in the eastern part 108-115 ppm (Table). The maximum permissible concentration of total arsenic in soil is 2ppm. Consequently, the total arsenic content in the soils of the dried-up bottom of the Aral Sea is many times higher than its maximum permissible concentration, which shows the high contamination of the soil with this dangerous element. Another dangerous heavy metal in the soil is chromium. According to the latest data, the danger of chromium is much higher than expected. The gross content of chromium in the soils of the dried-up bottom of the Aral Sea was higher at 0-shtab and 22 km than on the helipad and was 41.8; 37.6; 17.3 ppm, and in the eastern part - 27.9 - 36.9 ppm (Table). The maximum permissible concentration of the gross content of chromium in the soils of Uzbekistan has not been established. In the soils of the USA, the maximum permissible concentration of chromium reaches 240 ppm. The Clarke content of chromium in the soil is 70 ppm, in the lithosphere 83 ppm. In many cases, the maximum permissible concentration of gross chromium is 200 ppm. Then the ratio of the maximum permissible concentration to the Clarke index of chromium is 2.86. This value is within the accepted values (2-3) for the maximum permissible concentration of heavy metals. Consequently, the content of gross forms of chromium in the soils of the dried bottom of the Aral Sea is significantly lower than its Clarke and maximum permissible concentration. This indicates a safe content of chromium in the soils of the dried bottom of the Aral Sea.

The content of gross lead forms in the soils of the southern part of the dried-up bottom of the Aral Sea was 7.47-9.95 ppm, in particular in the 0-shtab - 8.00 ppm, at 22 km - 9.95 ppm, near the helicopter pad - 7.47 ppm. The content of gross lead forms in the eastern part of the Aral Sea was slightly higher than in the southern part and increased with increasing depth of the soil horizon, and the highest concentration of gross lead was observed in the 30-50 cm soil layer. Thus, the content of gross lead forms in the 0-10 cm soil layer of the eastern part of the Aral Sea was 8.51 ppm, in the 10-30 cm layer - 10.6 ppm, in the 30-50 cm layer - 12.4 ppm (Table). The Clarke of lead in the earth's crust is 16 ppm, in the soil 10 ppm, the maximum permissible concentration of total lead is 32 ppm. Consequently, the total content of lead is significantly lower than its maximum permissible concentration and within its Clarke. The amount of gross lead is slightly lower than its background concentration. Therefore, such a lead content does not pose any danger to the soil and the environment. But in the soils of the dried bottom of the Aral Sea, lead is contained in the form of salts, most of which are well soluble in water. This increases the harmful effect of lead and when they are transferred to other more fertile soils, for example, to irrigated soils.

The content of gross copper forms in the soils of the dried-up bottom of the Aral Sea was higher than its maximum permissible concentration. The maximum permissible concentration of gross copper forms in the soil is 55 ppm. The Clarke of gross copper forms for the lithosphere is 47 ppm, for the soil - 20 ppm, the content of background forms is 25 ppm. The content of gross copper forms in the soils of the 0-shtaba area in the southern parts of the dried-up bottom of the Aral Sea was 107 ppm, at 22 km - 148 ppm, near the helipad - 36 ppm. In the area where there is a helipad, the content of gross copper in the soil was significantly less than its maximum permissible concentration. In other places in the southern part of the Aral Sea, the content of gross copper was several times greater than its maximum permissible concentration. In the southern part of the Aral Sea, the content of gross copper forms in the soils of the dried bottom was within 81-124 ppm. The highest concentration of gross copper forms (124 ppm) in the eastern part of the Aral Sea was observed in the soil horizon of 10-30 cm. And in the 0-10 and 30-50 cm soil layers there were 81 and 84 ppm, respectively. Therefore, the soils of the dried bottom of the Aral Sea are contaminated with gross copper forms and, when the topsoil is transferred by the wind, can pollute the fertile irrigated soils located around the sea. Zinc is considered both an essential microelement and a heavy metal. Therefore, its concentration in the soil should be within narrow limits, which are considered optimal. A decrease in the zinc content compared to the optimal concentration leads to a decrease in crop yields, and an increase in the concentration of zinc than its upper limit contributes to the pollution of the soil and the environment. Therefore, the zinc content should be strictly within the optimal concentration. The total zinc content in all cases was below its maximum permissible concentration and Clarke. The Clarke of zinc in the earth's crust is 83, soil 50 ppm, the maximum permissible concentration is 100 ppm. The background concentration of total zinc for Uzbekistan is 70 ppm. In the southern part of the Aral Sea in the 0-shtab area in the 0-30 cm soil layer, the total zinc content was 24 ppm, at 22 km - 40 ppm, at the helicopter pad - 19.7 ppm. Consequently, in all places where soil samples were taken, the amount of total zinc is lower than its Clarke, maximum field concentration and background value. In the eastern part of the Aral Sea in the Koktash area, the total zinc content in the 0-10 cm soil horizon was 31.7 ppm, in the 10-30 cm horizon - 31.2 ppm, in the 30-50 cm layer - 37.2 ppm(Table). This total zinc content is lower than even its background value. However, the mobility of total zinc present in the soils of the dried bottom of the Aral Sea is high. Since, total zinc in these soils is represented by simple salts, most of which are well soluble in water. Another heavy metal that pollutes the soil is manganese. Manganese, on the other hand, is a microelement that actively participates in plant nutrition. Clarke of manganese in the earth's crust is 1000 ppm, in the soil 850 ppm, the maximum permissible concentration of total forms of manganese is 1500 ppm. The background content of gross manganese in the soil is 600 ppm. At the same time, in the soils of the eastern part of the Aral Sea, the content of gross manganese was higher than in the soils of the southern part. But in both parts of the Aral Sea, the content of gross manganese forms is much lower than its background content, Clarke and maximum permissible concentration. Although the proportion of the mobile form in its total amount can be high. Since manganese in these soils is mainly in the form of mineral salts. And in irrigated and rainfed soils of Uzbekistan, the content of the mobile form of manganese is very low. This is due to the fact that in carbonate soil conditions and with a slightly alkaline soil reaction, manganese very quickly passes into an immobile form. The content of gross manganese in the 0-shtab was 194 ppm, at 22 km - 296 ppm, near the helipad - 228 ppm. In the eastern part of the Aral Sea, the content of gross manganese forms in the soil horizons 0-10; 10-30 and 30-50 cm were 412; 357 and 468 ppm respectively.

In Uzbekistan, there is no maximum permissible concentration for the content of total and mobile iron in soil. The background content of total iron is 30,000 ppm. The Clarke of iron in the earth's crust is 51,000 ppm, in the soil - 38,000 ppm. In the soils of the dried-up bottom of the Aral Sea, the content of total iron forms was significantly lower than its background content and Clarke. In the soils of the southern part of the Aral Sea, the content of total iron was less than in the eastern part. For example, the amount of gross iron forms in the soil of the 0-shtab area was 8577 ppm, at 22 km - 15999 ppm, around the helicopter pad - 7557 ppm, in the eastern part of the Aral Sea in the Koktash area in the 0-10 cm soil horizon - 13089 ppm, in the 10-30 cm horizon - 12490 ppm, in the 30-50 cm soil horizon - 17471 ppm. In the carbonate soils of Uzbekistan, the content of mobile iron forms is very low and there is always a shortage of iron forms available for plants. Carbonates and alkaline soil reaction contribute to the transition of the available form of iron to the inaccessible form. Exactly the same processes occur with manganese compounds. Cobalt is contained in small quantities in the soils of Uzbekistan. The maximum permissible concentration of gross cobalt forms in the soil is 30 ppm. The cobalt Clarke in the lithosphere is 18 ppm, in the soil 8 ppm. The background content of cobalt in the soils of Uzbekistan is 10 ppm. In the soils of the dried-up bottom of the Aral Sea, the content of gross cobalt forms is significantly lower than its maximum permissible concentration and even the Clarke in the lithosphere and soil. The content of gross cobalt is much lower than its background content. In the southern part of the Aral Sea, in the 0-stack in the 0-30 cm soil layer, the content of gross cobalt forms was 3.19 ppm, in the 22-km - 5.49 ppm, around the helicopter pad - 2.34 ppm. In the eastern part of the Aral Sea, the content of gross cobalt in the soil horizon of 0-10 cm was 4.00 ppm, in the horizon of 10-30 cm - 4.58 ppm, in the soil layer of 30-50 cm - 5.95 ppm. Therefore, the content of gross forms of cobalt in the soils of the dried bottom of the Aral Sea is significantly lower than its maximum permissible concentration, Clarke and background content. But it should be taken into account that most of the cobalt in the soil of the dried bottom of the sea consists of simple mineral salts, which, in most cases, dissolve well in water.

Nickel is also considered a dangerous heavy metal that significantly pollutes soils. The maximum permissible concentration of total nickel forms is 85 ppm, Clarke of nickel in the lithosphere is 58 ppm, in the soil 40 ppm. The background content of total nickel forms in the soils of Uzbekistan is 40 ppm. The content of total nickel forms in the soils of the dried-up bottom of the Aral Sea is much lower than its maximum permissible concentration, Clarke in the lithosphere and soil and background content. For example, the content of total nickel forms in the soils of the dried-up bottom of the southern part of the Aral Sea in the 0-shtab area was 7.10 ppm, in 22 km - 16.8 ppm, around the helicopter pad - 5.46 ppm. In the eastern part of the Aral Sea in the Koktash area in the 0-10 cm horizon of the dried-out bottom soil the content of total nickel forms was 11.4 ppm, in the 10-30 cm soil layer - 13.4 ppm, in the 30-50 cm soil layer - 17.3 ppm. Consequently, the content of total nickel forms is significantly lower than its maximum permissible concentration, Clarke of the lithosphere and soil, as well as the background content. The content of total nickel forms in the soils of the dried-out bottom of the Aral Sea is in a safe position. But it will be necessary to take into account the probability of a high content of simple water-soluble nickel salts. Another of the heavy metals is molybdenum. Molybdenum, on the other hand, is considered a microelement necessary for plant nutrition. In carbonate and slightly alkaline soils of Uzbekistan, molybdenum has a relatively high mobility and its available forms in the soil are more or less increased. In acidic soils, molybdenum is mainly in an immobile form. Clarke molybdenum in the lithosphere and soil 3 ppm. The background content of gross forms of molybdenum for the soils of Uzbekistan is 1 ppm. The content of gross forms of molybdenum in the soils of the southern part of the dried bottom of the Aral Sea in the 0-shtab area was 4.76 ppm, at 22 km - 11.2 ppm, near the helipad - 4.02 ppm. In the eastern part of the Aral Sea in the Koktash area in the 0-10 cm soil layer the content of gross forms of molybdenum in the soils of the dried seabed was 3.40 ppm, in the 10-30 cm soil layer - 2.91 ppm, in the 30-50 cm soil layer - 2.91 ppm (Table). Consequently, the content of gross forms of molybdenum in the soils of the dried seabed is significantly higher than its Clarke in the lithosphere and soil, as well as the background content.

Table 1. Heavy metal content in the soils of the dried-up bottom of the Aral Sea

№	Soil sample collection location	Soil horizons, cm	Content of gross forms of heavy metals, ppm										
			Cr	Cd	As	Pb	Cu	Zn	Mn	Fe	Co	Ni	Mo
1	0-stab	0-30	41,8	0,031	184	8,00	107	24,00	194	8577	3,19	7,10	4,76
2	22 km	0-30	37,6	0,129	184	9,95	148	40,00	296	15999	5,49	16,8	11,2
3	Helipad	0-30	17,3	0,049	126	7,47	36	19,70	228	7557	2,34	5,46	4,02
4	Eastern part of	0-10	36,9	0,118	115	8,51	81	31,70	412	13089	4,00	11,4	3,40
5	the Aral Sea	10-30	27,9	0,042	108	10,60	124	31,20	357	12490	4,58	13,4	2,91
6	(Place Kuktash)	30-50	35,4	0,111	108	12,40	88	37,20	468	17471	5,95	17,3	2,91

Conclusion

Thus, the soils of the dried-up bottom of the Aral Sea contain heavy metals in quantities sufficient to pollute the environment. In particular, one of the dangerous heavy metals, arsenic, has a high content. The amount of arsenic significantly exceeds its maximum permissible concentration and background content. At the same time, the content of molybdenum also significantly exceeds its background amount and maximum permissible concentration. The same picture is observed with the content of copper. The content of gross copper is several times higher than its background content in the soils of Uzbekistan. The content of gross forms of chromium and cadmium in many cases slightly exceeds their background content. The content of gross forms of lead, zinc, manganese, iron, cobalt and nickel is significantly lower than their background content in the soils of Uzbekistan. But it is necessary to take into account the accumulation of heavy metals in the soils of the dried-up bottom of the Aral Sea as a result of the precipitation of simple mineral salts, which in most cases dissolve well in water. That is, in the total amount of heavy metals in the soils of the dried bottom of the Aral Sea, their mobile forms can occupy a significant place. Under such conditions, their danger increases significantly, and they become dangerous for organisms living in these places and in the surrounding areas.

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The influence of soil salinity in the shaulder irrigation area on autochthonous microorganisms

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Abstract

Background: According to the Agency for Land Management of the Republic of Kazakhstan, the total area of saline soils, solonetz and solonchaks occupies 41% of all soils in Kazakhstan. The aim is to study the autochthonous microbial community of saline soils to assess its condition and degree of degradation. Methods: Humus was determined according to the method of Tyurin, Isolation of autochthonous microorganisms from soil was carried out according to the method of E.Z. Tepper, identification by PCR. Results: The paper presents the results of the study of autochthonous microorganisms of saline soils of Shaulder irrigation massif of Turkestan region. It was found that with increasing degree of soil salinity the number of isolated microorganisms decreases. The highest value corresponds to soils with low salinity degree, in soils with medium and very high salinity degree their number decreases approximately in 2 times. There is an inverse dependence between humus content and number of microorganisms, which indicates their participation in the process of mineralization of humic substances. Taxonomic position of dominant species of autochthonous microorganisms in saline soils was determined. 25 morphotypes of autochthonous microorganisms were identified by PCR and their percentage content in the studied soils was determined. Conclusions: It has been established that the number of autochthonous bacteria and their species diversity decrease with increasing soil salinity. Autochthonous bacteria in saline soils are represented by the following phyla: *Actinobacteria*, *Proteobacteria* and *Firmicutes*, whose members are united by a common functional activity – transformation of complex, difficult to decompose organic matter, which include humus compounds. The activity of this group of bacteria can lead to humus losses in the soil.

Keywords: Saline soils, autochthonous microorganisms, morphotypes, identification.

Introduction

Soil salinization is one of the most acute problems of modern agriculture, occupying vast areas both in the world and in the Republic of Kazakhstan.

According to UNEP studies, about 20% of agricultural land and 50% of arable land in the world are subject to salinization processes (Paul et al.,2014). Acceptant to the Agency for Land Resources Management of the Republic of Kazakhstan, the total area of saline soils, solonts and solonchaks occupies 41% of all soils in Kazakhstan. The distribution of these soils is uneven. Most irrigated lands in the Republic of Kazakhstan are in its southern part, in the large deltas and ancient alluvial plains in the basins of the rivers Syr Darya and Ili

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(Małgorzata Suska-Malawska et al.,2022). Due to natural processes and anthropogenic impact, the area of saline soils increases every year. Moisture deficit and high salt content in the soil leads to its degradation and fertility reduction, resulting in losses of up to 40% of humus and secondary salinization processes (Saparov,2008). The autochthonous grouping of microorganisms in saline soils of Kazakhstan is poorly studied so far. The relevance of this study is mainly due to the possibility of using autochthonous microorganisms as an informative indicator of humus state of these soils in the process of ecological and biological monitoring, in planning agrotechnical measures and assessing their effectiveness. Currently, studies are being conducted to identify the correlation between the anthropogenic load on soils and the number of autochthonous microorganisms (Kulagina et al., 2021).

According to the definition of V. I. Kulagina, "autochthonous microorganisms are a trophic group of soil microorganisms capable of decomposing humus compounds of soil" (Kulagina et al., 2021). The study of autochthonous microbial community of saline soils is an important task for ecology. The use of microbiological indicators of soil activity allows to estimate its condition, degree of degradation quite accurately, and also allows to predict further changes in soil condition, especially in conditions of soil salinization.

Material and Methods

The objects of the study are samples of meadow-sierozem soils of different degrees of salinity, taken from the arable layer of the fields of Shaulder irrigation massif, located in Turkestan province of the Republic of Kazakhstan, which belongs to the arid regions of the country, where the level of evaporation exceeds the amount of precipitation about 10-20 times. According to Zhikhareva, "on the territory of the massif meadow-serozem saline (solonchak, in some places solonchak) soils prevail, under sparse grass-halophytic shrub vegetation with ephemerals and wormwood" (1969). The prevailing type of salinization on the territory of the massif is chloride-sulfate and sulfate-chloride sometimes with the presence of normal soda. All soils of the massif are carbonate and have high alkalinity (pH 8-9) (Savin et al., 2014). Our results indicate that the site soils have very low humus content indicating soil degradation, one of the factors of which is dehumification (Ibrayeva et al.,2021, 2020)

The methods generally accepted in soil science and soil microbiology were used in the work. Humus was determined according to the method of Tyurin I.V. (GOST 26213-2021). Identification of autochthonous microorganisms from soil was carried out according to the method of E.Z. Tepper, which consists in surface sowing of soil suspension on poor agarized mineral medium - nitrite agar (NA), prepared according to S.N. Vinogradsky for bacteria of the second phase of nitrification (Tepper et al., 2020, 2004). The number of microorganisms on NA was counted under a Zeiss Stemi 2000C stereomicroscope (Germany) by fields of view (Calculator of values. Electronic resource. 2022). The isolated pure cultures were identified by sequencing of the 16S rRNA gene region with universal prokaryotic primers 8UA: 5'-AGAGAGTTTGATCMTGGCTCAG-3', 519B: 5'-GTATTACCGCGGCGGCKGCTG-3' (Eurogen LLC, Russia). Amplification was performed on a Veriti 96-Well Fast Thermal Cycler DNA Amplifier (Life Technologies Corporation, USA). The taxonomic position of cultures was determined on the basis of the BLAST database (National Library of Medicine: Electronic resource. 2022)

Results

Our studies on determination of changes in the number of autochthonous microorganisms in soils of Shaulder irrigation massif under the influence of salinity factors and humus content (Table 1) have shown that with the increase of salinity degree their number decreases in medium- and very highly saline soils approximately 2 times in relation to the indicator of slightly saline soil.

There is an inverse relationship between humus reserves and the number of microorganisms of this group - the number of microorganisms decreases with increasing percentage of humus in the soil. The lowest abundance was observed in medium saline soil with relatively high humus content, and the highest - in very highly saline soil with minimum humus content (Table 1). This is an indirect evidence of microorganisms participation in the process of humus substances mineralization.

In different degrees of saline soils of Shaulder irrigation massif on the basis of culture features, 25 different morphological types of microorganisms were identified, which were then isolated in pure culture and identified by PCR method (Tables 2-4).

Table 1. Numbers of autochthonous microorganisms in meadow-sierozem soil of different salinity degree

Soil salinity degree	Humus, %	Numbers, CFU/g absolute dry soil	Numbers, CFU/g humus
Slightly saline	0,81	$105,1*10^4$ ($\pm 2,3*10^4$)	$129,8*10^6$ ($\pm 2,9*10^6$)
Medium saline	1,09	$50,3*10^4$ ($\pm 5,6*10^4$)	$46,2*10^6$ ($\pm 5,1*10^6$)
Very highly saline	0,39	$58,0*10^4$ ($\pm 38,0*10^4$)	$163,4*10^6$ ($\pm 97,5*10^6$)

Table 2 - Identification of pure cultures isolated from slightly saline soil sample

No. Morphotype	Species	Number of nucleotide pairs	Percentage of identity, %
2	Agromyces sp.	510	96,18
9	Rubrobacter sp.	502	92,31
16	Aerococcus viridans	525	96,17
18	Streptomyces harbinensis	488	99,11
21	Pseudomonas seleniipraecipitans	205	94,27
23	Agromyces ramosus	495	99,76
24	Pseudomonas stutzeri	511	99,54
25	Agromyces sp.	488	99,35

Table 3 - Identification of pure cultures isolated from a sample of medium saline soil

No. Morphotype	Species	Number of nucleotide pairs	Percentage of identity, %
9	Rubrobacter sp.	502	92,31
10	Pseudomonas stutzeri	514	99,53
14	Aeromicrobium sp.	490	99,51
16	Aerococcus viridans	525	96,17
25	Agromyces sp.	488	99,35

Table 4 - Identification of pure cultures isolated from a very highly saline soil sample

No. Morphotype	Species	Number of nucleotide pairs	Percentage of identity, %
12	Pseudomonas rhizosphaerae	490	99,36
16	Aerococcus viridans	525	96,17
18	Streptomyces harbinensis	488	99,11

The identification results can be considered reliable, which is confirmed by the high percentage of identity of the isolated strains with known species.

On the basis of the obtained data, diagrams demonstrating the composition of autochthonous microbial community of saline soils at the genus level (Figures 1- 3) were made.

In slightly saline soil, bacteria of the genera Streptomyces (16%), Agromyces (12%) and Rubrobacter (9%) dominate. The proportion of other identified morphotypes is less than 5%. The remaining strains could not be identified (Fig.1).

In medium saline soil, bacteria of genera Rubrobacter (16%), Pseudomonas (15%), Aerococcus (10%) dominate. The share of other morphotypes is 3 - 5% (Fig. 2).

In very highly saline soil (Fig.3) the highest percentage of bacteria of genus Aerococcus (42%) is observed. The share of representatives of other genera is less than 10%: Pseudomonas (8%); Streptomyces (4%).

Figure 1. Composition of autochtonus microorganisms in a sample of slightly saline soil

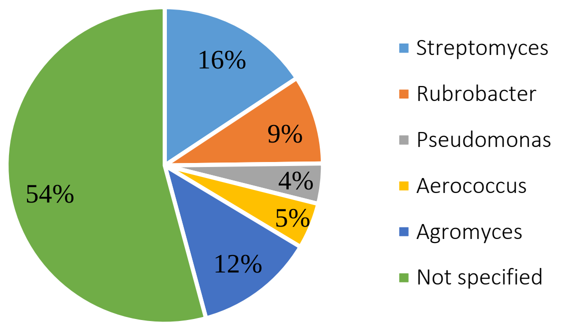
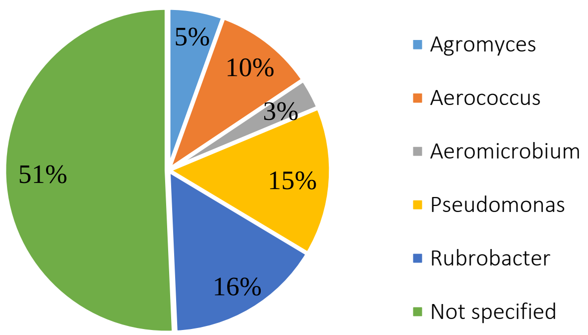


Figure 2. Composition of autochtonus microorganisms in a sample of medium salinity soil



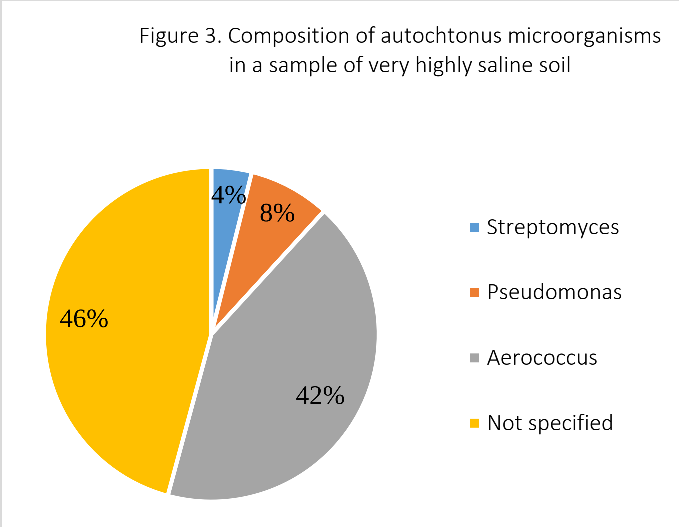


Table 5 - Taxonomic composition of autochthonous microorganisms in meadow-serozem soil of different salinity degree

Genus	Family	Class	Phylum
Agromyces	Microbacteriaceae	Actinobacteria	Actinobacteria
Streptomyces	Streptomycetaceae	Actinobacteria	Actinobacteria
Rubrobacter	Rubrobacteriaceae	Rubrobacteria	Actinobacteria
Pseudomonas	Pseudomonadaceae	γ-Proteobacteria	Proteobacteria
Aerococcus	Aerococcaceae	Bacilli	Firmicutes

Discussion

Aphthochthonous bacteria in meadow-sierozem saline soil represent a group of bacteria characteristics of this soil ecosystem capable of using difficult metabolizable soil substrates, primarily humus. The number of this grouping is high enough and makes 0,5-1,0 million cells in 1g of soil, and in terms of 1g of humus - 46,0 - 163,0 million depending on the degree of salinity and humus content. Autochthonous bacteria in the studied soils are represented by three phyla: Actinobacteria, Proteobacteria and Firmicutes. Actinobacteria are most represented, especially in slightly saline soil (5 species). They are mycelial prokaryotes, well tolerate drying and increased salt concentration due to their lipophilic cell wall, are capable of decomposition of organic matter difficult for other bacteria, produce various physiologically active compounds, and interact with plants. Pseudomonas bacteria, representatives of the phylum Proteobacteria, are widely distributed in saline soils. 3 species were identified in the studied soils. Pseudomonads possess catabolic versatility, ability to colonize plant roots, formation of enzymes and metabolites that increase plant stress resistance. One species from the phylum Firmicutes - Aerococcus viridans - was identified in all studied soils, the content of which increases with increasing salinity. Thus, the identified autochthonous bacteria fulfill important ecological functions in soil.

Conclusion

On the basis of the obtained data, it is established that with increasing degree of soil salinity the number of autochthonous bacteria and their species diversity decreases. The highest indicators correspond to the soil with a weak degree of salinization. It was revealed that there is an inverse relationship between humus content and the number of microorganisms, which indicates their participation in the process of mineralization of humus substances. Autochthonous bacteria in saline soils are represented by the following phyla: Actinobacteria, Proteobacteria and Firmicutes, representatives of which have unity of functional activity - decomposition of hard-to-access organic substances, which include humus compounds. The activity of this group can lead to humus losses in the soil.

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Soil fertility of tomato greenhouses in the Kaş region of Antalya

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Abstract

The material of this study, conducted in 2022, consists of 15 topsoil (0–30 cm) soil samples taken from greenhouses cultivating tomatoes in the Kaş district of Antalya province. In the soil samples, pH, electrical conductivity (salinity), organic matter (OM), lime, texture, total nitrogen, and available phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn) contents were analyzed. According to the coefficients of variation, the least variability was observed in soil pH (CV=1.99%), while the highest variability was found in the available sodium (Na) content (CV=154.02%). The highest salinity level (6.84 dS/m) was recorded in the sample with the highest available Na content (3029 mg/kg). All soil samples exhibited slightly to moderately alkaline characteristics. The available Cu content ranged between 3.79 and 22.14 mg/kg, and this high level of Cu is thought to originate from copper-based pesticides. It was determined that the available Mn and Zn contents were generally sufficient in the soil samples, while available Fe content was found to be insufficient. Furthermore, available phosphorus content was found to be very low in some soil samples, while lime content was found to be high.

Keywords: Greenhouse, soil fertility, soil properties, tomato, salinity.

Introduction

Tomato (*Solanum lycopersicum*) is among the most widely demanded vegetables year-round, necessitating its cultivation in both open-field and protected environments. In 2022, protected tomato cultivation in Turkey covered 25,830 hectares, yielding a total of 4,134,337 tons of table tomatoes. The Antalya-Kaş region accounted for 9.88% of this total production (TÜİK, 2025). Protected cultivation systems include not only traditional glass and plastic greenhouses but also low and high tunnel structures. Within these systems, tomato is grown using both soil-based and soilless cultivation techniques (Sönmez & Kaplan, 2007; Meriç et al., 2011; Toprak & Gül, 2013; Kartal & Gebeloğlu, 2023).

Tomato is not highly selective in terms of soil requirements and can grow in a wide range of soil types, from sandy soils to light clay soils (Ata, 2015). However, the most suitable soils for tomato cultivation are those with high water-holding capacity, sandy loam texture, rich in organic matter, low groundwater level, a pH between 5.5 and 7.0, and low salinity (less than 2.3 dS/m) (Karaköy, 2023).

In 2024, the average yield of greenhouse-grown table tomatoes in Turkiye was recorded at 91 tons per hectare. In the same year, Antalya province achieved a higher-than-average productivity with 104 tons per hectare, indicating its strong performance in protected agriculture. Within Antalya, the Kaş district reached a yield level of 120 tons per hectare in greenhouse tomato production. This production, carried out in fixed cultivation areas using glass and plastic greenhouses, highlights the positive influence of the region's climatic and physical conditions on agricultural productivity. This figure is approximately 32% higher than the

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national average and 15% higher than that of Antalya (TÜİK, 2025). These data clearly demonstrate the existence of significant regional yield differences in greenhouse tomato production, which should be taken into account in agricultural planning.

The aim of this study is to evaluate the soil properties of tomato greenhouses in the Kaş region of Antalya and to analyze the relationships among these properties.

Material and Methods

The soil samples were air-dried and passed through a 2-mm sieve. All analyses were conducted on these sieved samples. Particle size distribution was determined using the Bouyoucos hydrometer method (Bouyoucos, 1962). Selected soil properties—total soluble salts, organic matter content, $CaCO_3$, and pH—were analyzed according to Page et al. (1982). Total nitrogen (N) content and total soluble salts (TSS) were determined using a modified Kjeldahl method (Bremner, 1965). Available phosphorus (P) was measured using the molybdenum blue method in $NaHCO_3$ extract (Olsen et al., 1954). Available potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) were extracted with 1 N NH_4OAc and analyzed following Kacar (1994). Soil-available micronutrients—iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn)—were extracted with DTPA (diethylenetriaminepentaacetate) solution (Lindsay and Norvell, 1978) and analyzed using atomic absorption spectrophotometry (AAS) (Hanlon, 1992).

Results and Discussion

The analytical results and descriptive statistics of the soil samples analyzed in the study are presented in Tables 1 and 2.

Table 1. Descriptive statistical values of some physico-chemical soil properties.

Sampling number	pH	EC, dS/m	OM, %	$CaCO_3$, %	Sand, %	Silt, %	Clay, %
1	7.81	0.91	4.40	33.80	57	18	25
2	7.51	2.18	4.08	34.51	59	20	21
3	7.84	2.93	3.98	35.06	57	16	27
4	7.50	2.39	3.98	25.98	37	42	21
5	7.71	1.30	3.03	32.24	57	22	21
6	7.85	6.84	3.35	26.92	27	42	31
7	7.50	2.90	3.57	25.43	39	44	17
8	7.59	2.60	3.67	26.60	41	30	29
9	7.38	5.99	3.14	35.45	57	34	9
10	7.75	1.55	3.58	30.28	37	40	23
11	7.59	1.14	4.30	31.53	47	36	17
12	7.66	1.94	3.70	23.08	17	34	49
13	7.67	2.73	3.88	31.60	39	28	33
14	7.48	1.75	2.70	40.77	73	16	11
15	7.43	6.04	2.37	35.99	55	40	5
Mean	7.62	2.88	3.58	31.28	47	31	23
Minimum	7.38	0.91	2.37	23.08	17	16	5
Maximum	7.85	6.84	4.40	40.77	73	44	49
Std. Deviation	0.15	1.88	0.58	4.88	14.51	10.16	10.83
Skewness	-1.20	0.41	-0.07	-0.55	-0.04	-1.51	1.46
Kurtosis	0.15	1.26	-0.66	0.03	-0.29	-0.29	0.69
Coefficient of variation	1.99	65.35	16.11	15.60	31.13	33.00	47.91

In all soil samples, the soil reaction was found to be between slightly alkaline and moderately alkaline. Soil pH values ranged from 7.38 to 7.85, with an average of 7.62. Electrical conductivity (EC) values varied between 0.91 and 6.24 dS/m, with an average of 2.88 dS/m. The coefficient of variation for EC was 65.35%, indicating a high level of variability among the samples. According to Jones (2001), soils with EC values between 2-4 dS/m are considered moderately saline, while those with EC values between 4-8 dS/m are classified as saline. Based on this classification, most of the analyzed soil samples fall into the moderately saline and saline categories. A strong positive correlation was found between soil salinity and available sodium (Na) (Pearson's r = 0.804*; Figure 1, Table 3). Considering that greenhouse cultivation in the Antalya region is predominantly concentrated along the coastal strip between Kaş and Gazipaşa districts (Emekli et al., 2008), it is suggested that greenhouse soils may have been affected by seawater intrusion.

Table 2: Descriptive statistics of macro and micro nutrients.

	Total	Available								
Sampling number	N	P	K	Ca	Mg	Na	Fe	Cu	Zn	Mn
	%	mg/kg								
1	0.095	29.2	314.6	2781.9	1920	138.2	2.94	22.14	4.46	3.59
2	0.098	9.8	335.2	3171.2	1554	351.4	2.36	11.01	6.67	9.74
3	0.106	26.4	297.9	2923.5	1429	69.5	3.32	17.81	4.00	4.61
4	0.140	30.6	275.4	3771.9	3721	128.2	3.14	6.45	4.00	7.39
5	0.084	18.3	328.3	2373.6	1850	88.3	3.96	11.28	2.60	4.19
6	0.072	19.1	194.1	3508.1	3472	3029.2	5.66	5.04	2.73	7.70
7	0.101	31.4	267.5	3584.7	2979	147.4	3.15	6.27	3.69	8.05
8	0.090	1.6	277.3	3296.7	2645	524.8	2.77	4.20	0.63	6.13
9	0.112	10.2	423.8	3227.4	1837	858.6	1.98	6.48	4.81	7.98
10	0.095	28.8	265.5	3184.3	1897	124.2	1.87	15.40	3.66	8.69
11	0.078	24.6	520.4	3890.6	1839	95.1	5.87	9.24	1.78	7.97
12	0.106	5.2	382.2	4464.8	2924	214.3	2.13	4.32	4.39	7.31
13	0.078	1.8	237.1	3187.5	3044	521.7	2.52	3.79	0.95	6.16
14	0.096	2.1	182.3	3078.6	1067	137.5	2.16	5.78	1.21	4.51
15	0.117	9.7	484.7	3113.2	1826	935.3	1.84	7.04	4.30	8.86
Mean	0.098	16.59	319	3304	2267	490.3	3.04	9.08	3.33	6.86
Minimum	0.072	1.60	182	2374	1067	69.5	1.84	3.79	0.63	3.59
Maximum	0.140	31.40	520	4465	3721	3029.2	5.87	22.14	6.67	9.74
Std. Deviation	0.017	11.37	98	497	797	756.1	1.26	5.49	1.66	1.89
Skewness	1.24	-1.71	0.06	1.36	-0.94	10.27	1.41	0.92	-0.22	-1.00
Kurtosis	0.78	-0.04	0.76	0.59	0.47	3.06	1.44	1.30	-0.03	-0.43
Coefficient of variation	17.73	68.57	30.66	15.03	35.16	154.02	41.33	60.49	49.91	27.60

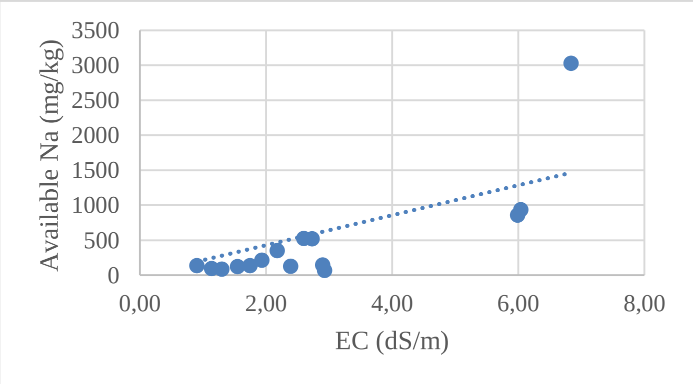

Figure 1: Relationship between soil salinity and available Na.

The organic matter content in the study area ranged from 2.37% to 4.40%, which, according to Emerson (1991) and Charman & Roper (1991), indicates that the soils have moderate to high levels of organic matter.

An examination of the particle size distribution of the soil samples revealed no accumulation in a specific fraction, with textures predominantly falling into the loam, clay loam, sandy clay loam, and sandy loam groups (Figure 2).

Among the three most commonly absorbed nutrients by plants - nitrogen (N), phosphorus (P), and potassium (K) - nitrogen exhibits the highest variability in the study area based on the coefficient of variation. This suggests that a certain level of uniformity in nitrogen fertilization practices has been established in tomato cultivation. Although phosphorus (P) exhibited high variability (CV=68.57%), the $CaCO_3$ content in the area showed relatively low variability (CV=15.60%). It is known that phosphorus can become unavailable to plants through fixation with lime. However, in this study, no significant relationship was found between $CaCO_3$ and phosphorus (Table 3). This suggests that the active carbonate content in the area may be variable. Another noteworthy finding is the relationship between phosphorus (P) and copper (Cu) in the soil. A significant positive correlation was observed between the two elements (Pearson's r=0.589). Pesticide use has been reported as one of the main causes of elevated copper (Cu) levels in soils (Li et al., 2020; Neaman et al., 2024).

Tablo 3: Pearson correlation coefficients between soil properties.

pH	-	EC	-0.202	OM	-	Clay	0.476	Sand	-	Zn	0.062	P	-	Mg	0.127
pH	-	OM	0.403	OM	-	N	-0.117	Sand	-	Mn	-0.350	P	-	Na	-0.148
pH	-	$CaCO_3$	-0.208	OM	-	P	0.406	Silt	-	Clay	-0.046	P	-	Fe	0.377
pH	-	Sand	-0.294	OM	-	K	0.008	Silt	-	N	0.189	P	-	Cu	0.589*
pH	-	Silt	-0.233	OM	-	Ca	0.247	Silt	-	P	0.268	P	-	Zn	0.302
pH	-	Clay	0.612*	OM	-	Mg	0.212	Silt	-	K	0.176	P	-	Mn	0.008
pH	-	N	-0.498	OM	-	Na	-0.283	Silt	-	Ca	0.573*	K	-	Ca	0.203
pH	-	P	0.333	OM	-	Fe	0.301	Silt	-	Mg	0.650**	K	-	Mg	-0.280
pH	-	K	-0.359	OM	-	Cu	0.403	Silt	-	Na	0.369	K	-	Na	-0.193
pH	-	Ca	-0.191	OM	-	Zn	0.132	Silt	-	Fe	0.165	K	-	Fe	0.055
pH	-	Mg	0.107	OM	-	Mn	-0.061	Silt	-	Cu	-0.466	K	-	Cu	0.059
pH	-	Na	0.198	$CaCO_3$	-	Sand	0.914***	Silt	-	Zn	0.016	K	-	Zn	0.310
pH	-	Fe	0.408	$CaCO_3$	-	Silt	-0.622*	Silt	-	Mn	0.675**	K	-	Mn	0.350
pH	-	Cu	0.522*	$CaCO_3$	-	Clay	-0.641*	Clay	-	N	-0.263	Ca	-	Mg	0.534*
pH	-	Zn	-0.137	$CaCO_3$	-	N	-0.021	Clay	-	P	-0.126	Ca	-	Na	0.084
pH	-	Mn	-0.447	$CaCO_3$	-	P	-0.220	Clay	-	K	-0.283	Ca	-	Fe	0.127
EC	-	OM	-0.515*	$CaCO_3$	-	K	0.108	Clay	-	Ca	0.415	Ca	-	Cu	-0.510
EC	-	$CaCO_3$	0.028	$CaCO_3$	-	Ca	-0.640*	Clay	-	Mg	0.486	Ca	-	Zn	0.038
EC	-	Sand	-0.122	$CaCO_3$	-	Mg	-0.841***	Clay	-	Na	0.075	Ca	-	Mn	0.496
EC	-	Silt	0.438	$CaCO_3$	-	Na	-0.151	Clay	-	Fe	0.105	Mg	-	Na	0.386
EC	-	Clay	-0.248	$CaCO_3$	-	Fe	-0.245	Clay	-	Cu	-0.062	Mg	-	Fe	0.245
EC	-	N	0.104	$CaCO_3$	-	Cu	0.331	Clay	-	Zn	-0.097	Mg	-	Cu	-0.495
EC	-	P	-0.191	$CaCO_3$	-	Zn	0.049	Clay	-	Mn	-0.165	Mg	-	Zn	-0.144
EC	-	K	0.076	$CaCO_3$	-	Mn	-0.261	N	-	P	0.188	Mg	-	Mn	0.213
EC	-	Ca	0.049	Sand	-	Silt	-0.666**	N	-	K	0.188	Na	-	Fe	0.386
EC	-	Mg	0.233	Sand	-	Clay	-0.714**	N	-	Ca	0.189	Na	-	Cu	-0.342
EC	-	Na	0.804***	Sand	-	N	0.063	N	-	Mg	0.085	Na	-	Zn	-0.056
EC	-	Fe	0.033	Sand	-	P	-0.094	N	-	Na	-0.320	Na	-	Mn	0.257
EC	-	Cu	-0.399	Sand	-	K	0.088	N	-	Fe	-0.516*	Fe	-	Cu	0.003
EC	-	Zn	0.146	Sand	-	Ca	-0.711**	N	-	Cu	0.002	Fe	-	Zn	-0.307
EC	-	Mn	0.393	Sand	-	Mg	-0.818***	N	-	Zn	0.516*	Fe	-	Mn	-0.081
OM	-	$CaCO_3$	-0.340	Sand	-	Na	-0.314	N	-	Mn	0.190	Cu	-	Zn	0.382
OM	-	Sand	-0.257	Sand	-	Fe	-0.195	P	-	K	0.013	Cu	-	Mn	-0.365
OM	-	Silt	-0.140	Sand	-	Cu	0.373	P	-	Ca	-0.036	Zn	-	Mn	0.414

* $p < .05$, ** $p < .01$, *** $p < .001$

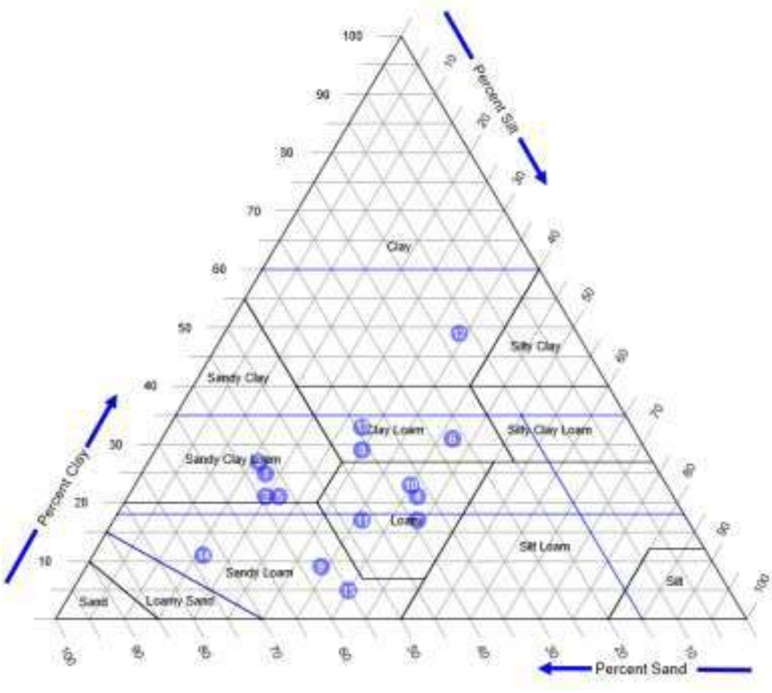

Figure 2. Particle size distribution of the soils in the study area.

Conclusion

High levels of salt and available sodium (Na) in the soil samples indicate potential problems related to irrigation water quality. In addition, the elevated copper (Cu) concentrations in the soils should be carefully evaluated in terms of both causes and consequences. Excessive Cu levels may exert a selective pressure on the soil microbiota (Fagnano et al., 2020). It has been reported that Cu toxicity can lead to phosphorus (P) deficiency (Feil, 2020). On the other hand, increased P availability may promote complexation and precipitation processes, thereby reducing the bioavailability of Cu and mitigating its toxicity to plants (Berghetti, 2022). In light of these findings, irrigation, fertilization, and plant protection practices in the region should be reconsidered in terms of their impacts on soil and human health.

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Effect of triacontanol (TRIA) applications on seed germination under salt stress conditions

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Abstract

Seed, the starting material of plant production, is also our basic food source. Increasing productivity and ensuring quality depends on the healthy germination of quality seeds. The ability of seeds to form seedlings while maintaining their viability under stress conditions is of great importance. Abiotic and biotic stress factors and seed-specific factors negatively affect yield by reducing germination and emergence rates. In particular abiotic stresses, restrict plant growth leads to serious crop losses on a global scale.Triacontanol (TRIA) acts as a signaling molecule during growth, increases seed metabolism and germination distribution, as well as ensuring plant development under stress conditions. It also has positive effects on development, productivity and quality. However, the germination effects of TRIA, especially under salt stress, have been investigated limitedly. While it increases germination in some plants, it has been reported that it may cause negative impacts in some species. Applications of TRIA in saline environments is important research topic, current studies demonstrate the potential of this substance to alleviate stress effects. In this review, the effects of TRIA on seed germination under salt stress were investigated. Studies have shown varying results on the germination rates of TRIA application. Future research will further elucidate the stress tolerance-enhancing effects of TRIA. The use of TRIA can offer a sustainable approach to increasing agricultural yield and quality.

Keywords: Plant growth regulator, salinity, seed, seed germination, triacontanol (TRIA).

Introduction

One of the main factors limiting productivity in agriculture is abiotic stresses. Factors such as low/high temperature, drought, salinity, excessive moisture, heavy metals and oxidative stress negatively affect plant development, preventing the use of genetic potential and leading to serious losses in agricultural production (Bray et al., 2000; Yavas and Ilker, 2020). This situation threatens sustainable plant production and causes financial losses on a global scale. In order to cope with such stress conditions, the use of plant growth regulators (PGRs) has gained importance (Zaid and Mohammad, 2018).

Triacontanol (TRIA) was isolated from alfalfa stalks in 1933 (Chibnal et al., 1933) and its growth-promoting effects were first documented in 1959. This natural 30-carbon primary alcohol, with the molecular formula $CH_3(CH_2)_{28}CH_2OH$, has a straight-chain structure (Ries et al., 1977). TRIA, whose synonyms include melacyl alcohol, miraculan, and myricyl alcohol, is generally known commercially as Miraculan, with the trade name

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Mixatalol. Commercial formulations of TRIA are available as Vipul and Miraculan (Mishra and Shrivastava, 1991).

It is a substance found naturally in living things that enables plant growth. It is known that TRIA supports biomass production by increasing photosynthesis, protein synthesis, soluble sugar and amino acid levels, and positively affects processes such as rooting, germination, flowering and fruit set. It is also an effective, non-toxic growth regulator at low doses (Karacakaya, 2009). TRIA, unlike other growth regulators, has been reported to have yield-enhancing effects even under stress conditions (Verma et al., 2022). However, these effects may vary depending on the species, application dose and stress factors.

Effect of Tria On Seed Germination Under Salt Stress Conditions

The effects of salt stress on agricultural production are devastating. Salt accumulation in agricultural lands is increasing due to reasons such as salt water infiltration into the soil, irregular irrigation, soil erosion and inadequate natural drainage (Dassanayake and Larkin 2017; Ahmad et al. 2018; Kumar and Saddhe 2018). This situation limits plant growth by negatively affecting seed germination, root and stem development, water balance and photosynthesis.

Seed germination requires the coordination of different physiological and biochemical processes. Interactions between hormones play critical roles in determining the speed and rate of germination. Triacontanol (TRIA) stands out as a potential regulator in this process; however, there is still limited information in the literature on its interaction with other plant hormones and its mechanism in salt stress (Ahmad et al., 2016; Per et al., 2018; Jogawat, 2019).

Cavusoglu et al. (2007) reported that TRIA pretreatment had statistically significant effects on germination and seedling development in plants exposed to salt stress. However, it has also been observed that germination is suppressed at high salinity levels. This shows that the effect of TRIA may vary depending on the application dose, stress severity and plant species.

Effect of Tria Applications on Plant Growth in Salt Conditions

Salinity suppresses plant growth by reducing seed germination, root and stem elongation, fresh weight and water content (Kabar ve Baltepe, 1987; Gulzar ve Khan, 2002; Dash ve Panda, 2001; El-Mashad and Kamel 2001). Some studies have reported that TRIA promotes germination in plants species such as maize, rice and sunflower (Niranjana et al., 1999), while in some plant species (e.g. lettuce) it has been reported to negatively affect germination (Lewak and Skowrońska, 1982). Similarly, the effects on root and stem growth have also been reported to be inhibited or promoted by TRIA depending on the application dose and plant species (Somen and Seethalakshmi 1991, Kumaravelu 2009).). Research shows that TRIA application supports plant growth under salt stress. TRIA provides positive effects in this process by increasing photosystem II efficiency, chlorophyll content, CO_2 fixation, and gas exchange parameters (Baba et al., 2017).

In the study conducted by Aziz and Shahbaz (2015), it was determined that salt stress induced by 150 mM NaCl reduced the dry weight of shoots and roots in sunflower varieties, and at the same time, there was a decrease in the activities of antioxidant defense enzymes such as peroxidase (POD) and superoxide dismutase (SOD). However, foliar application of TRIA reduced these adverse effects and contributed to growth promotion in both sunflower cultivars. This finding suggests that TRIA may provide physiological protection against salt stress.

Effect of Tria on Physiological and Biochemical Properties of Plants Under Salt Stress

TRIA application has significant effects on the physiological and biochemical properties of plants under salt stress conditions. TRIA applied to leaves has been shown to affect various physiological and biochemical processes under this stress (Perveen et al., 2013).

TRIA not only improves plant development and physiological-biochemical processes, but also increases the quality characteristics, nutritional content and yield of various crops (Naeem et al., 2009; 2010; 2011). TRIA affects the biochemical pathways that regulate stress responses in plants; it supports nitrogen fixation, carbonic anhydrase enzyme activity and the accumulation of various metabolites (free amino acids, soluble proteins and sugars), thus increasing the plant's capacity to survive under stress. (Li et al., 2016).

TRIA application has been shown to significantly enhance plant stress tolerance by increasing photosynthetic efficiency, enhancing antioxidant enzyme activity, regulating osmotic balance, and promoting nutrient uptake. This compound increases the content of photosynthetic pigments, promotes the accumulation of compatible osmolytes, and strengthens the antioxidant defense system, providing plants with an advantage in coping with oxidative damage and osmotic imbalances caused by environmental stresses. (Zulfiqar and Shahbaz, 2013; Khedr, 2017).

Many studies show that TRIA alleviates the negative effects on plant performance under salt stress and strengthens tolerance mechanisms by re-regulating metabolic activities. Selected studies reporting the plant supportive effects of TRIA against salt stress are summarized in Table 1.

Table 1. Some literature studies on salinity stress and TRIA (Zaid et al 2020; Sharma and Dhriti 2023; El-Beltagi et al 2025).

Salt Conditions	TRIA Application	Plant Species	Plant Response	Reference
NaCl (0.25M)	10μM	*Raphanus sativus*	Salt stress induced by 0.25 M NaCl led to a reduction in stem diameter, epidermal cell size, cortical thickness, vascular bundle width, cambial cell thickness, as well as xylem, phloem, and tracheal diameters. In contrast, leaf reduction was associated with an increase in epidermal cell number and cell width.	Cavusoglu et al., (2008)
NaCl(10, 15, 20, 25 and 30 mM)	10 mM	*Glycine max*	TRIA treatment led to increases in leaf area, leaf weight ratio, and relative water content in plants. Furthermore, enhancements in chlorophyll pigment concentration, nucleic acid levels, total soluble sugars, and protein content were observed. Notably, TRIA application helped restore normal metabolic activities in soybean plants subjected to salt stress conditions.	Krishnan and Kumari (2008).
NaCl (25, 75 and 150 mM)	11.2 μM	*Zea mays*	NaCl reduced plant growth, SPAD index, and protein content. TRIA ameliorated growth reduction and increased nitrogen assimilation, activities of antioxidant enzymes, flavonoids, phenols, and proline.	Ertani et al. (2013)
NaCl (150 mM)	10 and 20 μM	*Triticum aestivum*	Salt stress caused a significant reduction in growth, net photosynthetic rate, transpiration rate, chlorophyll content (Chl a and b), and chlorophyll fluorescence parameters. Among the treatments, TRIA at a concentration of 10 μM was the most effective in mitigating the adverse effects of salinity stress across various growth stages.	Perveen et al. (2013)
NaCl (0, 150 mM)	0,50,100μM	*Helianthus annus L.*	TRIA application in sunflower increased shoot and root fresh weights and length, transpiration rate, water use efficiency, stomatal conductance and assimilation rate in both saline and control conditions.	Aziz et al. (2013)
NaCl (0, 100, and 150 mM)	0,5 ve 1 mg L^{-1}	*Brassica napus L.*	Pre-sowing TRIA application to seeds increased shoot fresh weight, seed number per plant, photosynthetic rate, transpiration rate, chlorophyll a/b ratio, and electron transport rate. Furthermore, K^+ content and free proline and glycine betaine levels in shoots and roots were also increased under both saline and non-saline conditions.	Shahbaz et al. (2013)
NaCl (0,75 ve 150 mM)	0, 10 ve 20 μM	*Coriandrum sativum L.*	Application of TRIA (10 μM) as a foliar spray promoted growth by enhancing antioxidant enzyme activities, thereby effectively alleviating the detrimental effects of salt stress.	Asadi Karam and Keramat (2017)
NaCl (100 mM)	2 and 5 μM	*Zea mays*	NaCl (100 mM) stress decreased growth parameters and increased membrane permeability, MDA, proline, and Na+ contents, and POD and CAT activities. Leaf TRIA (2 and 5 μM) ameliorated growth inhibition and increased soluble proteins, NRA, secondary metabolites, proline, and shoot K+ contents. TRIA (5 μM) was much more effective under optimum and salt stress conditions.	Perveen et al. (2017)
NaCl (50, 100 and 150 mM)	10^{-6} M	*Mentha arvensis*	Triacontanol significantly promoted growth, enhanced the accumulation of essential mineral nutrients, and improved both yield and quality traits.	Khanam and Mohammad (2018)
Salinity (50 mmol L^{-1})	0.80 mg L^{-1}	*Cucumis sativus L.*	TRIA treatments mitigated the adverse effects of salt stress by increasing CO_2 uptake, gas exchange, stomatal conductance, chlorophyll content, transpiration rate, water use efficiency, nutrient uptake, and photosynthetic activity. They also further increased SOD, POD, and CAT in all cucumber genotypes.	Sarwar et al. (2021)
NaCl (250 mM)	1μM	*Spinacia oleracea L.*	Treatment with 1 μM TRA significantly alleviated salt-induced inhibition of growth and photosynthesis under 250 mM NaCl stress by stimulating metabolic processes, thereby mitigating the deleterious effects of salt stress.	Tompa and Fodorpataki (2021)
NaCl (75 mM)	0, 25, 50 ve 75 μM	*Capsicum annuum*	TRIA treatment enhanced gas exchange parameters, chlorophyll and carotenoid contents, and proline accumulation. Activities of SOD and CAT were significantly increased, whereas MDA and H_2O_2 levels were markedly reduced. Under salt stress, root and shoot lengths reached their maximum with 50 μM TRIA treatment, accompanied by enhanced APX activity.	Sarwar et al. (2022)

NaCl (50, 100 and 150 mM)	150 µM	*Brassica juncea* L.	Foliar application of 150 µM TRIA significantly improved growth parameters, including root and shoot length, as well as fresh and dry biomass under salt stress conditions. Furthermore, TRIA treatment enhanced protein content, levels of metabolites such as flavonoids, phenolic compounds, and anthocyanins, and activities of antioxidant enzymes (APX, CAT, PPO, GPX), thereby strengthening the antioxidant defense system.	Verma et al. (2023)
Salt Stress	0, 10 ve 20 µM	*Punica granatum*	Application of TRIA resulted in elevated concentrations of mineral nutrients (N, P, K, Ca), increased relative water content, and enhanced activities of antioxidant enzymes including CAT, POD, and SOD. Furthermore, TRIA treatment boosted levels of glycine betaine, proline, amino acids, total phenolics, and carbohydrates, which were associated with significant improvements in fruit weight and yield.	Khedr and Khedr (2024)

Discussion

Triacontanol (TRIA) is an effective plant growth regulator that promotes growth in stressed plants, increases germination rates and improves yield. It can increase the tolerance of plants to salt stress, especially supporting photosynthesis, mineral uptake and antioxidant defense mechanisms. However, these effects may vary depending on the TRIA dose used, the application method, and the plant species.

Therefore, further experimental studies are needed to develop species-specific and condition-specific research on the use of TRIA. Considering the increasing population, decreasing agricultural areas and climate change, natural regulators such as TRIA are among the promising tools for sustainable agriculture.

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Boosting lettuce yield and soil quality with fermented plant fertilizers

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Abstract

This research evaluated the impact of three plant-based extracts Aloe vera, Nettle (Urtica dioica), and Purslane (Portulaca oleracea), applied at varying concentrations (0%, 0.5%, 1.0%, 1.5%, and 2.0%) on soil quality dynamics. The experiment was conducted under greenhouse conditions using a completely randomized design (CRD) to evaluate different indicators such as soil pH, electrical conductivity (EC), organic matter (OM), basal soil respiration (BSR), microbial biomass carbon (MBC), nitrogen, and available phosphorus. All treatments led to notable improvements in microbial function, organic matter, nutrient levels. Regard to Purslane extract, demonstrated at (1.0% – 2.0%) was the most effective, improving soil pH, E.C, and phosphorus levels. Nettle extract also showed improvements in MBC, especially at 1.5–2.0%. On the other hand, Aloe vera extract (1.0–1.5%) enhanced positively BSR and total nitrogen. In conclusion, the strategic application of plant-based extracts especially Purslane and Nettle at 1.0–2.0% serves as a sustainable method to improve soil parameters. These findings advocate for the use of plant-based biostimulants as part of eco-friendly fertilization strategies that minimize reliance on chemical inputs.

Keywords: Fermented plant extracts, lactuca sativa, soil quality, soil biological health, organic fertilization.

Introduction

Modern agriculture faces the dual challenge of ensuring high crop productivity while preserving the ecological functions of soils. According to Doran and Zeiss (2000), soil health is defined as the capacity of soil to function as a living system, supporting both plant productivity, animal productivity and nutrients cycling, maintaining the environmental quality. However, the widespread use of synthetic fertilizers has led to negative impacts such as soil degradation, nutrient imbalances, and increased greenhouse gas emissions (Tahat et al., 2020; Bashir et al., 2013). These concerns highlight the urgent need for sustainable alternatives.

Plant-based materials used as organic fertilizers have emerged as effective alternatives to synthetic fertilizers. Over the last years, they have gained recognition as sustainable substitutes for synthetic inputs enhancing soil fertility by increasing organic matter levels, stimulating beneficial microbial populations, and minimizing environmental impact (Kiełbasa et al., 2018). Liquid fertilizers not only provides readily available nutrients and moisture but also contain bioactive compounds with growth-promoting and antimicrobial effects

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(Akinyemi et al., 2018). Aloe vera, nettle (Urtica dioica), and purslane (Portulaca oleracea) are particularly notable for their rich biochemical profiles and environmental friendliness, positioning them as valuable tools in sustainable nutrient management.

Aloe vera (syn. Aloe barbadensis Miller) is reocognized for its high water retention capacity and biochemical diversity. Its extract is packed with beneficial compounds such as amino acids, vitamins, minerals, enzymes, proteins, polysaccharides, and phytohormones, all of which contribute to enhancing plant development and boosting soil microbial activity (Akinyemi et al., 2018). Urtica dioica, widely known as nettle, is a rich plant that provides essential elements such as nitrogen, potassium, calcium, and magnesium. Research has highlighted its role in improving soil quality and increasing vegetable yields in organic agriculture (Di Virgilio et al., 2015). Similarly, Portulaca oleracea (purslane) is appreciated for both its adaptability across different climates and its high levels of bioactive compounds such as vitamins, flavonoids, lignans, and alkaloids which exhibit antimicrobial and antioxidant properties (Ferreira et al., 2024).

This research investigates and compares the impact of fermented liquid extracts derived from Aloe vera, Urtica dioica, and Portulaca oleracea on soil properties. The study contributes to identify effective organic alternatives that promote sustainability in agricultural systems.

Material and Methods

Study Site and Soil Characteristics

The experiment was conducted under controlled greenhouse conditions at the Faculty of Agriculture, Ondokuz Mayıs University, located in Samsun Province, Türkiye (41°21′49.9″ N, 36°11′19.7″ E).

A comprehensive pre-analysis of the soil was conducted to determine its physical and chemical properties before the application of treatments. The soil results show essential characteristics (Table 1)

Table 1. Preliminary physio-chemical analysis of soil

Soil Properties	Results
pH (1:1)	7.18
EC, dSm $^{-1}$	0.91
Texture class	Clay
Clay, %	46.96
Silt, %	24.33
Sand, %	28.69
Organic matter, %	2.26
Lime ($CaCO_3$) content, %	0.97
Total N, %	0.26
Available P, ppm	46.95
Exchangeable K, cmol kg $^{-1}$	1.90
Available Na, cmol kg $^{-1}$	0.71
Available Ca, cmol kg $^{-1}$	29.40
Available Mg, cmol kg $^{-1}$	24.0

Preparation of Plant-Based Extracts

The plant-based extracts applied in this research were fermented for a period of two months, allowing natural microbial activity to decompose organic materials and increase nutrient availability. This process involved the spontaneous participation of microorganisms such as bacteria, fungi, and yeasts that facilitated the transformation of raw plant matter into nutrient rich solutions.

Experimental Design and Treatments

The experiment used a Completely Randomized Design (CRD) with three types of plant extracts (Aloe vera, Nettle, Purslane) applied at four concentrations (0.5%, 1%, 1.5%, 2%) plus three unfertilized controls. Each treatment got three replicates, obtaining a total of 39 pots.

Statistical Analysis

All collected data were analyzed using Microsoft Excel and OriginPro. A two-way Analysis of Variance (ANOVA) was conducted to determine significant treatment effects. Means were compared using Tukey's HSD test at the 5% significance level ($p \leq 0.05$). Results are reported as mean ± standard error.

Results and Discussion

Among the treatments, Aloe vera at 1.5% (T3) showed the highest soil pH value (7.70), followed closely by Purslane at 2.0% (T4). The control group recorded the lowest value (7.40), while all extract treatments showed pH levels above this baseline. Nettle extract also led to a measurable pH increase, though less pronounced compared to Aloe vera and Purslane. On the other hand, the highest EC value among Aloe vera treatments was recorded at 1.0% (T2), but differences across doses remained minimal. Nettle-treated soils showed similarly stable EC values at all application rates. Conversely, Purslane extract showed a dose-dependent increase in soil EC, with the highest value observed at 2.0% (T4), reaching 876.5 µS cm^{-1}.

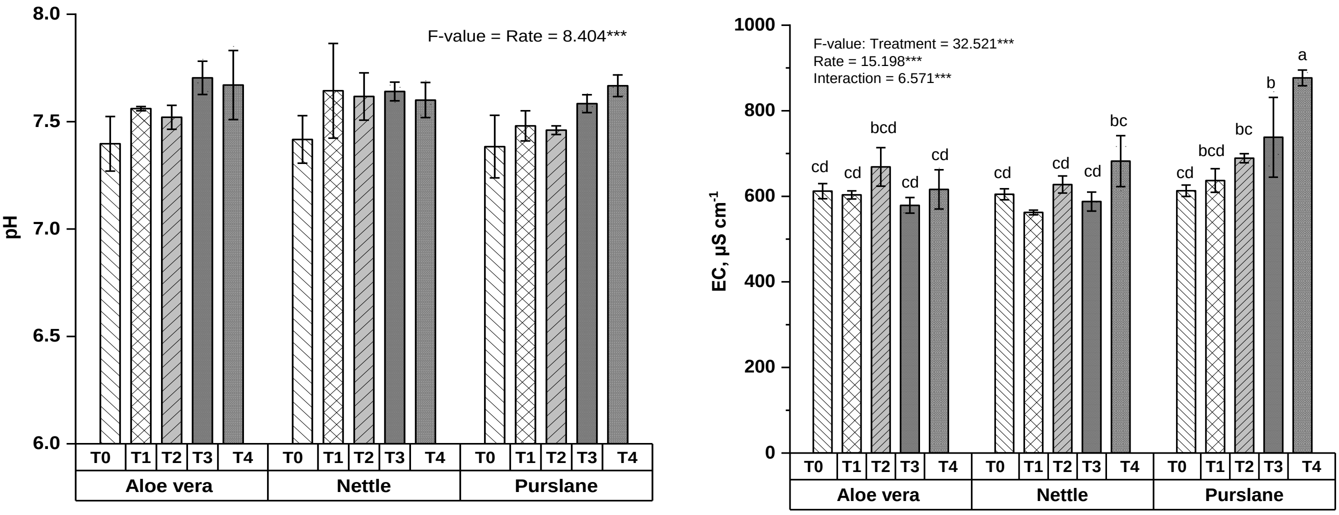

Figure 1. Effects of different concentrations (0.5%, 1.0%, 1.5%, and 2.0%) of plant extracts on pH and EC

Peterson and Jensen (1985), who observed that nettle extract raised soil pH in acidic soils, thereby improving nutrients .However, care must be taken to ensure that pH increases remain within the optimal range for crop growth, as excessive alkalinity may reduce the availability of certain micronutrients such as iron, manganese, and phosphorus. Yazdani-Biouki et al. (2023) points out that purslane has phytoremediation potential to regulate soil EC under saline stress, suggesting that its effect on EC is concentration-dependent. While moderate use may enhance nutrient availability, excessive application may risk salt accumulation in sensitive soils.

Effects on soil OM and BSR

All treatments resulted in higher OM content compared to the control (T0). Aloe vera at 1.0% (T2) yielded the highest value at 3.7%, indicating a potential peak effect at moderate doses. Similar trends were observed in Nettle and Purslane treatments, where lower concentrations (T1–T2) led to improved OM content. While for BSR among the treatments, Aloe vera at 2.0% (T4) showed the highest respiration rate (0.15 mg CO_2 g^{-1} 24 h^{-1}), followed by Purslane at the same dose (0.13 mg CO_2 g^{-1} 24 h^{-1}). Nettle extract also produced consistent enhancements in BSR at 0.5% (T1) and 1.5% (T3), suggesting a beneficial effect at moderate doses.

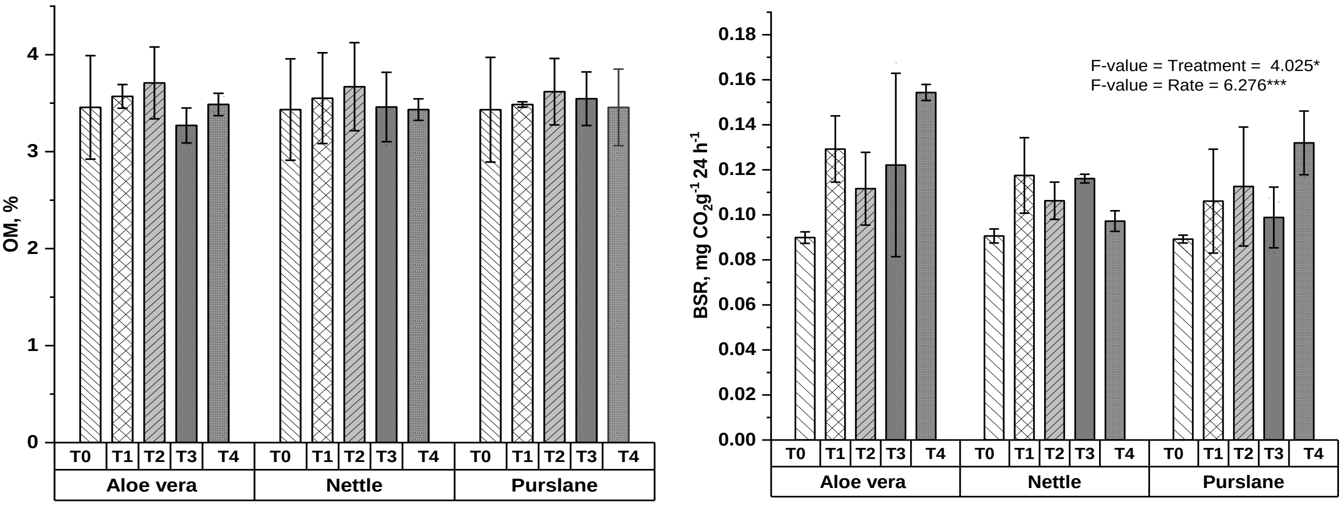

Figure 2. Effects of different concentrations (0.5%, 1.0%, 1.5%, and 2.0%) of plant extracts on OM and BSR

These results align with Luo et al. (2018), who found that organic fertilizers boost soil organic matter (OM). Khater et al. (2020) showed that Aloe vera combined with organics increased biomass and nutrient return, aiding OM buildup. Sindhu et al. (2022) highlighted plant extracts' role in stimulating microbial activity and OM accumulation through bioactive compounds. Regard to BSR the findings suggest that higher concentrations of organic amendments stimulate microbial respiration, likely due to the increased availability of labile carbon compounds that serve as energy sources for soil microbes.

Effects on microbial biomass carbon

Among all treatments, it is evident to observe an enhancement in MBC compared to the control group, indicating suitable amount of carbon contained in the living microbial biomass in the soil and suggesting that the extracts generally stimulated microbial activity. Nettle extract at 1.5% (T3) and 2.0% (T4) showed the highest MBC levels, reaching 51.42 mg CO_2 g^{-1} soil 24 h^{-1} and 49.21 mg CO_2 g^{-1} soil 24 h^{-1}, respectively. This suggests that nettle may provide readily available substrates or bioactive compounds that promote microbial proliferation and metabolic activity. Whereas, the lowest MBC value was observed in Purslane at 0.5% (T1), with 38.34 mg CO_2 g^{-1} soil 24 h^{-1}.

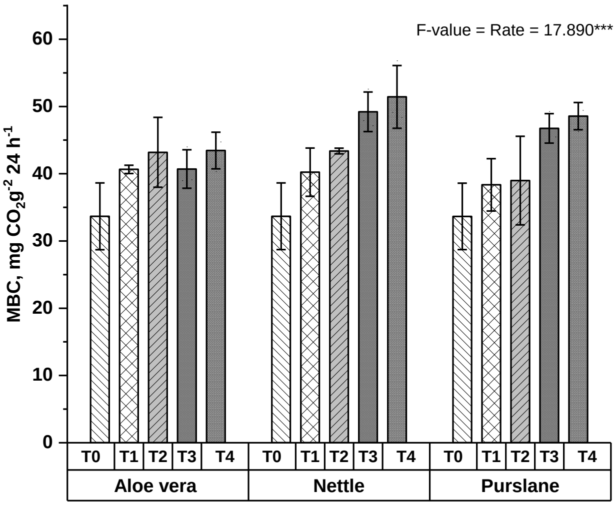

Figure 3. Effects of different concentrations (0.5%, 1.0%, 1.5%, and 2.0%) of plant extracts on MBC.

Effects on total nitrogen and phosphorous

Among all treatments, the lowest total nitrogen values were recorded under Purslane at 0.5% and Aloe vera at 1.5% and 2.0%, pointing out potential nitrogen immobilization or limited mineralization at these application levels. Nettle treatments, particularly at 0.5%, showed more stable nitrogen values across all doses, with only a slight dip at 1.0% (T2), suggesting more consistent nitrogen dynamics compared to the other extracts. Moreover, Purslane at 0.5% (T1) resulted in the highest available phosphorus content, reaching 63 ppm, followed by 1.0% (T2) with 59.55 ppm. Nettle extract also showed a positive effect at 1.5% (T3), getting 54.70 ppm, while Aloe vera consistently exhibited the lowest phosphorus concentrations across all doses. The control group (T0) maintained a baseline phosphorus level of approximately 22.78 ppm, showing limited natural variation in available phosphorus.

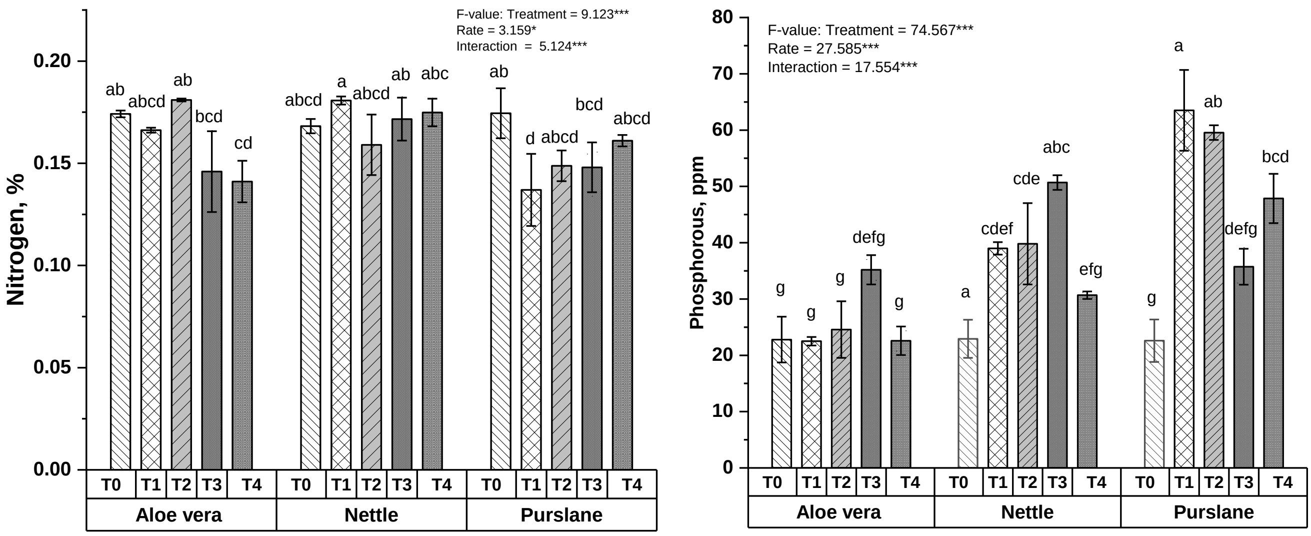

Figure 4. Effects of different concentrations (0.5%, 1.0%, 1.5%, and 2.0%) of plant extracts on nitrogen and phosphorous

Carrascosa-Robles et al. (2024) found that purslane combined with legume residues improved soil nitrogen and microbial activity. In contrast, Lanouar et al. (2018) reported that Aloe vera reduced nitrogen and phosphorus availability but increased CEC, indicating its stronger effect on other soil properties. Likewise a study by Pavinato et al. (2008), demonstrated that plant's compounds can significantly increase phosphorus levels in soil. The results highlight the potential of plant-based extracts especially low-dose. Purslane treatments effectively enhanced soil phosphorus levels without causing nutrient imbalances, supporting their integration into nutrient management strategies that promote balanced C–N–P cycling and minimize environmental impact.

Conclusion

This study evaluated the impact of three fermented plant-based extracts: Aloe vera, Nettle (Urtica dioica), and Purslane (Portulaca oleracea) applied at different level concentrations on soil quality under controlled greenhouse conditions. The results revealed that concentrations ranging from 0.5% to 2.0% notably improved both soil biological activity and plant growth performance, highlighting their potential as sustainable alternatives to chemical fertilizers. Among all the treatments, Purslane extract was the most effective overall, particularly at 1.5–2.0%, where it significantly enhanced soil pH, electrical conductivity (EC), and phosphorous content. Nettle extract also demonstrated strong biostimulant properties at moderate to high levels, boosting microbial biomas carbon (MBC), thereby supporting nutrient cycling and soil microbial health. In addition, Aloe vera extract (1.0–1.5%) enhanced positively BSR and total nitrogen. Nevertheless, it also contributed to increased microbial and enzymatic activity. In summary, plant-derived biostimulants especially Purslane can effectively enhance both crop productivity and soil health when applied in moderate to high concentrations. Further field research is recommended to validate these results under diverse environmental conditions.

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Land Degradation in Agricultural Soils in Zile District, Tokat

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Abstract

Land degradation poses a serious threat to environmental sustainability and the livelihoods of millions of people, especially in developing countries. Land degradation generally refers to the deterioration of land quality and productivity caused by human activities such as deforestation, overgrazing, and unsustainable agricultural practices. The aim of this study is to determine the state of land degradation in agricultural lands located in the Tokat Zile Plain, which has a semi-arid terrestrial ecosystem. For this purpose, 175 surface (0-30 cm) soil samples were taken to represent the 1,667-ha research area. To determine soil degradation, the physical and chemical indicators of the soils were analyzed, including crust formation, K Erodibility, bulk density, hydraulic conductivity, sand, silt, clay, pH, EC, and organic matter indicators, totaling 10 indicators.

Keywords: Land degradation, soil, Tokat

Introduction

The continuous and rapid growth of the world's population has led to increasing pressure on natural resources. Therefore, it is of great importance to plan and implement sustainable agricultural practices on soils, which are among the most essential natural assets required for agricultural production. In our country, the growing demand for land use has resulted in the unplanned, uncontrolled, and non-agricultural utilization of fertile agricultural lands, which in turn gives rise to various environmental problems. One of these problems manifests itself as land degradation.

Land degradation is defined as the decline in land productivity that affects the integrity of ecosystems through processes such as erosion, salinization, and the loss of soil fertility. These processes are accelerated by activities such as deforestation, overgrazing, intensive agriculture, and urbanization. Globally, approximately 92% of degraded land results from inappropriate agricultural practices and the large-scale conversion of land for agricultural and other industrial purposes, encompassing an area of about 18.1 million km^2.

Soil resources constitute the foundation for human survival and development. Land resources are a non-renewable asset for humankind. Land degradation refers to the decline in the biological productivity of drylands, semi-arid areas, humid regions, grasslands, rangelands, forests, and wetlands, resulting from human activities or the combined influence of various factors. Land degradation also encompasses wind and water erosion, which lead to the loss of soil material and the long-term depletion of natural vegetation (Warrena, 2002). It involves the deterioration of soil properties related to crop production, infrastructure maintenance, and natural resource quality (Lal, 2001). Furthermore, it is associated with the progressive reduction of ecosystem productivity over time (Turner, 2016). This condition arises from soil acidification, alkalinization, nutrient depletion, loss of soil organic matter (SOM), compaction, soil erosion, and the decline of biodiversity.

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Land degradation also occurs through a variety of physical, biological, and chemical processes that are directly or indirectly induced by human activities. Desertification, as a phenomenon of land degradation, refers to the transformation of fertile soils into deserts due to aridification. Both land degradation and desertification affect human health in multiple ways. As a consequence, lands deteriorate, desert areas expand, food production decreases, and the depletion of water resources compels populations to migrate to vulnerable regions.

The rate of soil and land degradation increases in parallel with the pace of land cover deterioration. Factors such as vegetation cover, land use and distribution, as well as the management of these soils, play a significant role in the occurrence of land degradation. In conclusion, disasters such as floods and droughts are becoming increasingly severe, posing a serious threat to human survival and development. At present, the core focus of land degradation research includes assessment and monitoring based on diverse data sources, prevention and ecological restoration, identification of driving factors through various methods at different scales, and the simulation and prediction of development trends using quantitative models. The present study aims to evaluate land degradation in the agricultural areas located in Tokat and its Zile District.

Material and Methods

Geographically, Tokat Province is located between 36°00'–36°42' east longitudes and 39°52'–40°55' north latitudes. It is bordered by Samsun to the north, Ordu to the northeast, Sivas to the south and southeast, Yozgat to the southwest, and Amasya to the west. With a surface area of 1,002,399 km^2, it is the fourth largest province in the Black Sea Region. The study area is situated in the Central Black Sea Region within the borders of Tokat Province, specifically in the Zile Plain, located 70 km west of the provincial center. It is one of the most important plains with a semi-arid climate, allowing for intensive agricultural activities. The study area covers approximately 1,667 ha and is located between 75°18'00"–75°42'00" E and 45°04'00"–45°24'00" N (UTM, Zone 36-m) coordinates. It is bordered by Turhal District to the east, Göynücek District of Amasya Province to the north, Artova District to the south, and Çekerek District of Yozgat Province to the west.

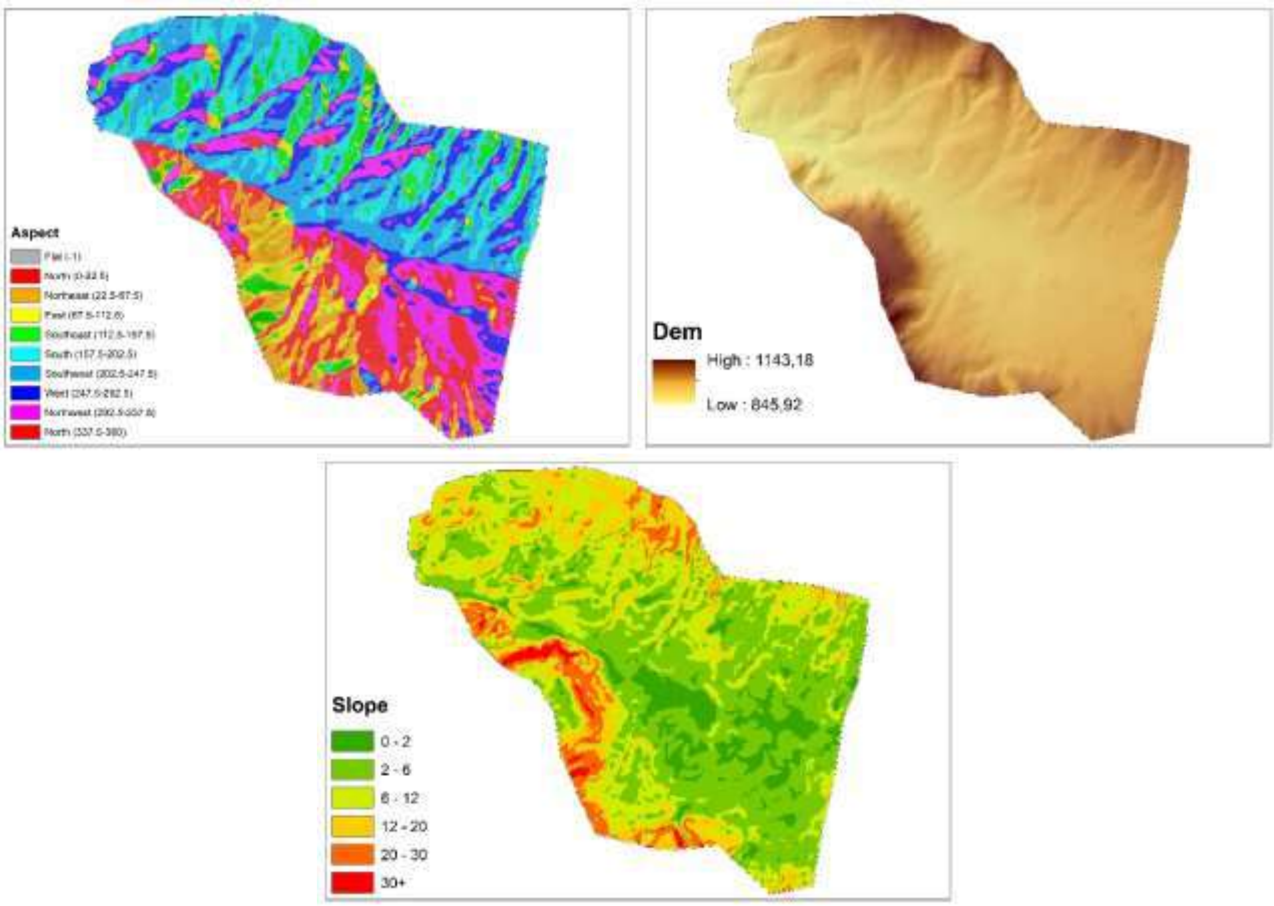

Figure 1. Digital elevation contours derived from 1:25,000 scale topographic maps were used to generate the digital elevation model (DEM), aspect, and slope maps of the study area, which are presented in Figure 1. The elevation of the study area ranges between 845 m and 1143 m above sea level, with altitude increasing towards the northern and southern parts of the area. This increase in elevation also results in steeper slopes, with steep and very steep slopes (greater than 20%) observed particularly in these sections. In contrast, nearly flat slopes (0–2%) and gently sloping areas (6–12%) are distributed across the central and southeastern parts

of the study area. Examination of the aspect characteristics reveals that south and southwest-facing slopes are predominant within the area, followed by those with northern and northeastern orientations.

The area is predominantly characterized by the distribution of limestone formations, while the central parts are mainly composed of alluvial deposits transported by the river. In the southern sections of the area, albeit in limited amounts, the presence of spilite-tuff rocks is observed.

Within the scope of this study, various descriptive parameters were employed to examine the soil properties in the sampling area in order to better understand the characteristics of the soils. These parameters include the maximum value, minimum value, standard deviation, coefficient of variation, mean value, skewness, and kurtosis. The calculations were performed using the SPSS software (IBM, 2015). In addition, geostatistical methods were applied to determine the spatial distribution of soil properties within the study area. In this context, ten selected parameters will be used to assess land degradation in the study area, and distribution maps for the entire area will be generated based on the data obtained from these calculations.

In order to generate the distribution maps of the region, the ArcGIS 10.5 version of the geographic information system software was utilized. This software is a powerful tool for processing and analyzing geographic data, and it is particularly well-suited for visualizing and analyzing spatial distributions. Prior to the mapping process, the properties of the data that did not exhibit a normal distribution were corrected through appropriate transformations. During the map generation stage, the Inverse Distance Weighting (IDW) method was employed. This method is used to produce spatial distribution maps by taking into account the surrounding influence of data points.

Land degradation indicators will be converted into dimensionless scores ranging from 0.1 to 1.0, enabling their comparison through standard scoring functions. In the literature, three general types of scoring functions are commonly employed: "more is better," "less is better," and "optimum at midpoint" (Karlen and Stott, 1994; Masto et al., 2008; Liu et al., 2018). In this study, the application of the "more is better" function implies that higher scores for a given indicator represent the criterion that least influences land degradation, thereby demonstrating the maximum potential effect it can exert. Conversely, the application of the "less is better" function suggests that lower scores indicate the complete reduction of a property that positively influences land degradation, thereby reflecting the outcome of its minimal presence. Within the scope of this study, the "more is better" function was applied to organic matter, clay, pH, EC, and hydraulic conductivity, while the "less is better" function was applied to silt, sand, bulk density, K erodibility, and crust formation.

Table 1. Standart scoring functions of land degradation

Scoring	Indicator	L	U	Standart Scoring Function
More Is Better	Organic Matter	0.18	6.40	$f(x) = \begin{cases} 1 & x \leq L \\ 1 - 0.9\,x\,\frac{x-L}{U-L} & L \leq x \leq U \\ 0.1 & x \geq U \end{cases}$
	Clay	9.42	58.15	
	pH	7.11	8.83	
	EC	0.1019	1.085	
	Hydraulic Conductivity	0.13	70.41	
Less Is Better	Silt	6.13	33.47	$f(x) = \begin{cases} 1 & x \leq L \\ 1 - 0.9\,x\,\frac{x-L}{U-L} & L \leq x \leq U \\ 0.1 & x \geq U \end{cases}$
	Sand	27.81	83.86	
	Bulk Density	1.32	1.62	
	K Erodibility	0.101	0.719	
	Crust Formation	0.69	9.43	

Result and Discussions

In total, 175 soil samples were collected from the study area, and sixteen physical, chemical, and biological soil properties were examined. The descriptive statistics of these properties are presented in Table 2. The soil samples were generally classified as non-saline (0–1.08 dS/m) in terms of salinity, while the soil reaction ranged between neutral and slightly alkaline (7.11–8.83).

Based on the sand, silt, and clay contents, the soil texture classes were identified as clay loam (14.85%), sandy clay loam (18.28%), clay (52%), sandy loam (3.42%), sandy clay (9.75%), loam (1.14%), and loamy sand (0.57%). According to Kacar (2009), the soils' organic carbon contents were determined to range between low and high classes, while aggregate stability values varied between 10.62% and 96.30%, corresponding to low and high levels. Accordingly, among the soil properties of the study area, soil pH, bulk density (BD), and soil water content (SWC) exhibited "low" variability with less than 15% coefficient of variation. In contrast, electrical conductivity, sand, clay, silt, aggregate stability, carbon, soil organic carbon, and organic matter showed "high" variability, exceeding 35% relative to the mean.

Table 2. Descriptive statistics of soil properties

Parameters	Mean	S:D	%COF*	Variance	MV	HV	Ske.**	Kur.
pH	7.67	0.19	2.47	0.03	7.11	8.83	1.37	7.96
EC (dS/m^{-1})	0.52	0.15	28.84	0.02	0.10	1.08	0.77	1.70
Sand (%)	42.97	9.50	22.10	90.25	27.81	83.86	1.38	2.41
Clay (%)	39.15	9.05	23.11	81.97	9.42	58.14	-0.65	0.333
Silt (%)	17.87	4.00	22.38	16.05	6.13	33.47	0.39	3.50
OC (%)	1.22	0.66	54.09	0.44	0.10	3.71	1.01	1.89
AS (%)	54.92	14.87	27.07	221.26	10.62	96.30	-0.04	0.10
BD g/cm^3	1.44	0.06	4.16	0.004	1.32	1.62	0.52	0.07
SWC (%)	11.65	1.09	9.35	1.19	4.10	13.79	-3.24	15.80
OM (%)	2.11	1.15	54.50	1.32	0.17	6.40	1.01	1.89

The overall aim of the study was to ensure that values that theoretically have the least positive effect on land degradation receive higher scores, while those that have the greatest positive effect receive lower scores. As a result, the spatial distribution of land degradation obtained through standard scoring is presented in Fig 2.

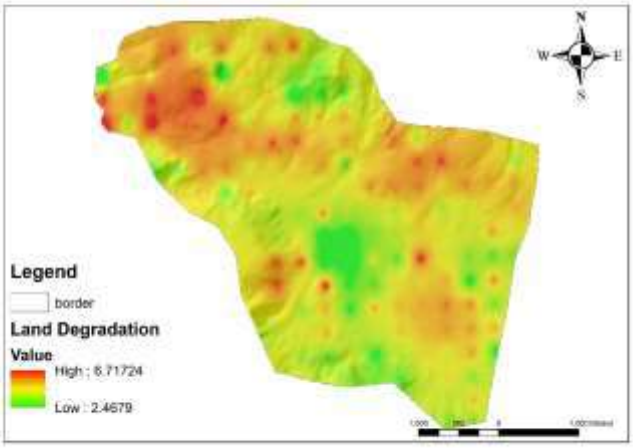

Figure 2. SSF Land degradation map

The land degradation values of the study area were determined to range from a minimum of 2.467 to a maximum of 6.717. It was observed that the southern parts of the area exhibit lower land degradation values, whereas the northern parts display higher values. Central areas were found to contain zones with low to moderate land degradation. Consequently, it can be inferred that the northern sections of the area are more susceptible to land degradation, while the southern sections are comparatively in a better condition under the given circumstances.

Conclusion

In this study, the land degradation status of agricultural fields in the Zile District of Tokat was assessed using standard scoring. Based on the collected samples, the relationship between the physical and chemical properties of the soils and land degradation was examined. This approach demonstrated that if soil properties theoretically considered to have low impact on land degradation receive high values in the standard scoring, and those considered to have high impact receive low values, the resulting influence on land degradation across the area can be determined.

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Effect of Tomato Residue Compost Application, Alone and Combined with Mineral Fertilization, on Exchangeable Base Cations in Soil under Greenhouse Tomato Cultivation

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Abstract

Excessive reliance on mineral fertilizers can impair soil quality, whereas organic amendments such as composts may improve soil chemical fertility and contribute to more sustainable tomato production. In this greenhouse pot experiment, we evaluated the effects of tomato residue compost (TC) applied at 1, 2, 4, and 6% (w/w), either alone or combined with an optimum mineral fertilizer dose, on selected soil chemical properties with emphasis on exchangeable base cations (Na, K, Ca, Mg). The experiment was conducted using a clay loam, slightly alkaline, moderately calcareous soil with low organic matter. Treatments consisted of a control, mineral fertilizer alone, TC at four rates, and TC at four rates combined with mineral fertilizer (10 treatments), arranged in a randomized design with three replications. Destructive soil sampling was performed at three tomato growth stages: first flowering, first harvest, and final harvest. Across the sampling stages, compost-amended soils generally showed increases in exchangeable base cations, with the most pronounced and consistent response observed for exchangeable K and Mg, reflecting the contribution of compost-derived nutrients and exchange reactions. Exchangeable Ca displayed a stage- and dose-dependent pattern, while exchangeable Na tended to be highest at the final harvest stage. Because composts may increase not only K, Ca, and Mg but also Na and related salinity/sodicity risks if not properly monitored, compost quality (including soluble Na) and soil chemical indicators should be evaluated alongside crop responses. These findings support the use of tomato residue compost—particularly in integrated programs with mineral fertilization—to enhance soil nutrient status under greenhouse tomato cultivation, while emphasizing the need for monitoring Na dynamics and overall soil fertility changes.

Keywords: Tomato residue compost; organic amendment; exchangeable cations; potassium; sodium; greenhouse; soil fertility

Introduction

Agricultural intensification increasingly seeks to maximize productivity per unit area; however, long-term or excessive use of mineral fertilizers can contribute to deterioration of soil quality and create environmental concerns. Organic amendments—particularly composts produced from agricultural residues—represent a practical strategy to recycle nutrients and organic matter back into soils and to partially substitute mineral fertilizers in sustainable cropping systems. In Türkiye, low soil organic matter is widely recognized as a major

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fertility constraint, reinforcing the need for organic inputs and residue recycling strategies (Kacar, 1986; Pilanalı, 2001).

Soil organic matter is a central driver of soil chemical, physical, and biological functioning, and organic amendments are widely used to increase organic matter inputs and improve soil fertility. Studies in tomato production systems have shown that organic amendment type can markedly influence soil properties and plant performance, including changes in soil organic matter and exchangeable nutrients that can translate into improved tomato growth under certain amendments (Su et al., 2022). Beyond farmyard manure, the agricultural use of plant-derived wastes and agro-industrial residues has been emphasized as a practical route to improve soil fertility and reduce dependence on mineral fertilizers (Kacar et al., 1996; Kütük and Çaycı, 2000). Composts can also modify soil chemical fertility through their effects on exchangeable base cations and cation exchange capacity (CEC). For example, application of organic compost to soils has been reported to increase exchangeable K, Ca, Mg, and Na, and to elevate CEC and base saturation—effects that can be agronomically beneficial but require monitoring to avoid unintended salinity/sodicity issues (Abreu Jr., et al., 2001). In greenhouse tomato systems, nutrient removal with post-harvest plant residues can be substantial; therefore, composting and returning these residues to soil has been recommended as a sustainable nutrient-recycling pathway (Sönmez et al., 2002).

Among the exchangeable cations, potassium is particularly relevant because composts often contain considerable K, and K can participate in exchange reactions that influence the distribution of Na on exchange sites. Mechanistic work indicates that compost-derived K can replace Na adsorbed by electrostatic attraction and by stronger chemical interactions, thereby affecting sodium dynamics in soils; however, the direction and magnitude of Na change depend strongly on compost composition, especially the soluble K/Na balance (Tong et al., 2021). Dose-dependent changes in exchangeable cations and related fertility indicators following compost-based amendments have also been reported under controlled cultivation conditions (Aydinşakir et al., 2011; Tamer et al., 2016).

Tomato production is sensitive to nutrient imbalances and to salinity-related constraints; therefore, understanding how tomato residue compost affects exchangeable cations during crop growth is important for designing integrated fertilization programs. In this context, the present study aimed to determine the effects of tomato residue compost applied at increasing rates, alone and combined with mineral fertilizers, on soil exchangeable Na, K, Ca, and Mg at key tomato growth stages under greenhouse conditions.

Material and Methods

Experimental Soil

Soil used in the greenhouse pot experiment was collected from long-term cultivated farmland in Bafra District (Samsun, Türkiye). The composite soil sample was air-dried under shade, gently crushed, and passed through a 2 mm sieve prior to analysis and pot filling. Baseline physical and chemical properties were determined using standard procedures (Table 1).

Table 1. Methods used to determine soil properties in the greenhouse experiment (Jackson, 1956).

Analyses	Methods
Soil texture	Hydrometer method
Soil reaction (pH)	pH meter in 1:1 (w/v) soil:distilled water suspension
Electrical Conductivity (EC)	EC meter in 1:1 (w/v) soil:distilled water suspension
Organic matter	Walkey-Black method
Lime ($CaCO_3$)	Volumetric determination with Scheibler calcimeter
Total N	Kjeldahl method
Available P	Olsen method
Exchangeable Na, K, Ca, Mg	1 N NH_4OAc extraction
Available Fe, Cu, Zn, Mn	0.05M DTPA + 0.01M $CaCl_2$ + 0.1M TEA extraction

The soil was classified as clay loam with slightly alkaline reaction and moderate lime content, low organic matter, and no sodicity risk based on initial exchangeable Na.

Tomato residues and compost production

Tomato residues were collected from tomato-growing fields in Ağıllar Village (Bafra District, Samsun). Composting was performed aerobically using the windrow method as previously described (Durmuş and Kızılkaya, 2018). The composting period lasted 90 days; the compost was packaged and stored prior to use. To improve application uniformity, compost was sieved through a 4 mm mesh before incorporation into soil.

Recommended strengthening (to be added as a short Table): Compost quality characterization should include pH, EC, organic carbon, total N, C/N ratio, and macro/microelement composition, because compost chemistry strongly governs cation responses and Na-related risks. Standard compost characterization commonly includes these parameters and can be aligned to routine protocols.

Plant material

"F1 determinate tomato" seedlings were used. Seedling age at transplanting, planting density (one plant per pot), and greenhouse environmental conditions should be specified (temperature, relative humidity, irrigation schedule) to ensure reproducibility.

Experimental design and treatments

The experiment was conducted in pots containing 3.5 kg soil each. Treatments were arranged in a randomized design with three replications. In total, 90 pots were established: 3 sampling stages × 10 treatments × 3 replications = 90.

Table 2. Greenhouse experiment treatments

	Applications
1	Control
2	Chemical fertilizer application (optimum dose*)
3	Compost application (1%)
4	Compost application (2%)
5	Compost application (4%)
6	Compost application (6%)
7	Compost application (1%) + Chemical fertilizer application *
8	Compost application (2%) + Chemical fertilizer application *
9	Compost application (4%) + Chemical fertilizer application *
10	Compost application (6%) + Chemical fertilizer application *

*Mineral fertilizer dose per pot (based on soil analysis): 3.36 g ammonium sulfate, 2.07 g TSP, and 1.24 g K_2SO_4

Sampling strategy and laboratory analyses

Soil samples were collected destructively at three tomato growth stages: (i) first flowering, (ii) first harvest, and (iii) final harvest. For each sampling stage, soils were analyzed for exchangeable Na, K, Ca, and Mg using 1 N NH_4OAc extraction, consistent with the baseline methods (Table 1). (If plant growth/yield parameters were collected, these should be presented and statistically tested alongside soil data.)

Statistical analysis

Data should be analyzed separately by sampling stage (because pots were destructively sampled), using ANOVA under the chosen experimental design, followed by mean separation (e.g., LSD at $P < 0.05$). This approach is consistent with compost–soil studies that evaluate compost and combined treatments under greenhouse conditions with replicated designs.

Results and Discussion

Initial soil properties

Key baseline soil properties are summarized in Table 3. The soil was clay loam, slightly alkaline (pH 7.55), non-saline (EC 1.02 dS m^{-1}), low in organic matter (1.64%), and moderately calcareous (11.19% $CaCO_3$). Exchangeable Ca dominated the exchange complex, followed by Mg and K, and exchangeable Na was low, indicating no sodicity risk at the start.

Table 3. Some properties of the soil used in the experiment

pH	EC (dS/m)	Clay (%)	Silt (%)	Sand (%)	O.M. (%)	$CaCO_3$ (%)
7,55	1,02	29,94	43,50	26,56	1,64	11,19
Total N (%)	**P (ppm)**	**Na (meq/ 100 gr)**	**K (meq/ 100 gr)**	**Ca (meq/ 100 gr)**	**Mg (meq/ 100 gr)**	
0,13	6,29	0,254	0,568	31,84	8,88	

Exchangeable sodium (Na)

Exchangeable Na dynamics across growth stages are shown in Figure 1. The highest exchangeable Na generally occurred at the final harvest stage, and across treatments Na often increased, while in some cases it remained unchanged or decreased. An increase in exchangeable Na after compost addition has been reported in controlled experiments and can reflect Na inputs from the compost itself and/or displacement reactions on exchange sites. For example, compost application has been shown to increase exchangeable Na alongside other base cations, emphasizing the need for monitoring chemical changes and potential risks when applying composts (Abreu Jr. et al., 2001). Similar Na increases (or Na behavior comparable to mineral fertilization) have been documented under different amendment and compost–mineral fertilization scenarios, indicating that Na responses are amendment- and soil-dependent (Özdemir et al., 2014; Rosinski, 1970). From a mechanistic standpoint, compost effects on Na depend strongly on compost chemistry. Evidence indicates that compost-derived K can replace exchangeable Na (both weakly and strongly held fractions), reducing Na under certain compost types; however, when compost is abundant in water-soluble Na, Na removal may not occur and exchangeable Na may increase (Tong et al., 2021).

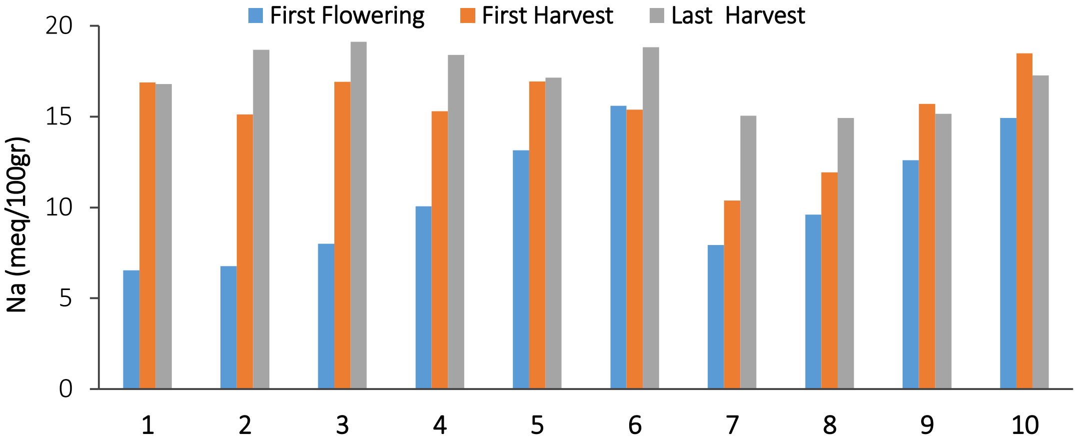

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Figure 1. Exchangeable sodium content of soils after the experiment

Exchangeable potassium (K)

Exchangeable K results are presented in Figure 2. Potassium was generally highest at the first flowering stage and decreased thereafter. This pattern is consistent with crop physiological demand, where K uptake accelerates during flowering and peaks during fruit development, potentially reducing soil exchangeable K in later stages. Compost application plausibly increased exchangeable K because plant residues and composts can serve as K sources and can increase exchangeable K in soil. Studies in tomato systems indicate that organic amendments, particularly composts, can increase soil exchangeable K and improve tomato growth, supporting integrated organic amendment use in tomato cultivation (Su et al., 2022). A similar stage-linked nutrient uptake dynamic in tomato, including changes in nutrient demand during flowering and fruiting, has been reported previously (Huett and Dettmann, 1988). Moreover, increases in soil K following organic soil conditioner applications have been reported under field conditions, supporting the role of organic inputs in improving exchangeable K availability (Tamer et al., 2016).

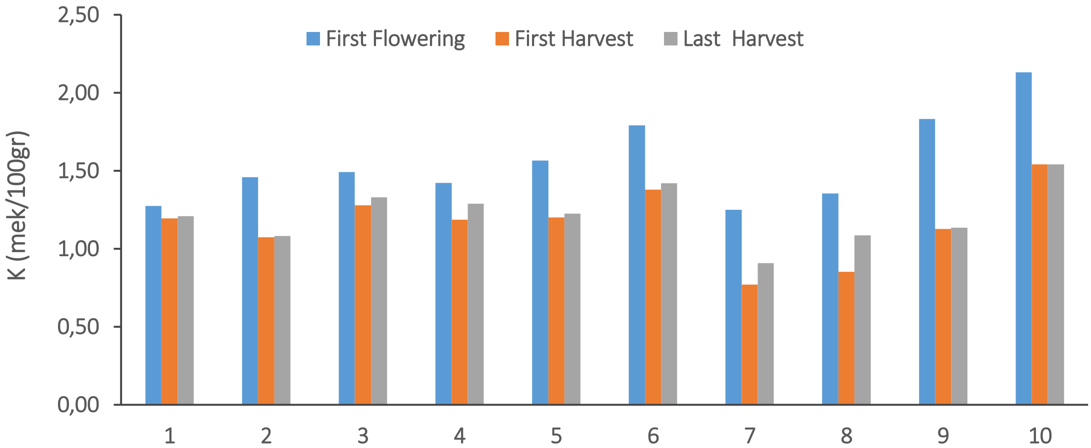

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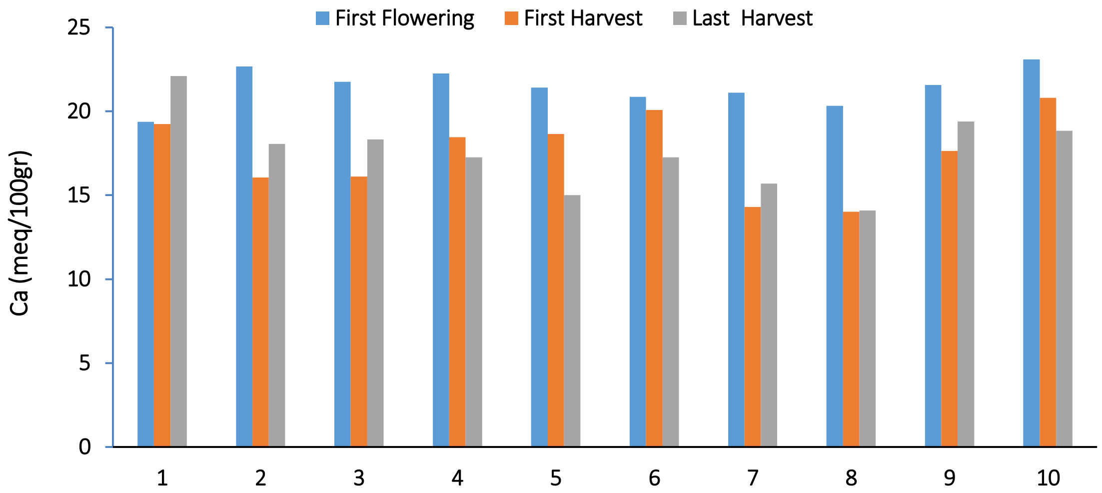
Figure 2. Exchangeable potassium content of soils after the experiment

Exchangeable calcium (Ca)

Exchangeable Ca trends are shown in Figure 3. Soil Ca was generally highest at the first flowering stage; thereafter, Ca responses appeared dose- and stage-dependent, including increases at first harvest under some treatments and decreases by final harvest. Because Ca is critical for tomato fruit quality (e.g., prevention of blossom-end rot), Ca dynamics should be interpreted in conjunction with plant uptake and yield/fruit data (if measured). Compost effects on Ca can occur through direct Ca addition, changes in CEC, and competition among cations on exchange sites. Broadly, compost application can increase exchangeable Ca alongside other base cations and can modify CEC, which influences the exchange complex composition (Abreu Jr. et al., 2001). Comparable increases in soil Ca following organic amendments (e.g., biochar derived from agricultural residues) have also been reported, indicating that residue-based amendments can alter Ca status depending on material properties and application rate (Namlı et al., 2017).



1: Control 2: Chemical Fertilizer(CF) 3: % 1 Compost 4: % 2 Compost 5: % 4 Compost 6: % 6 Compost 7: % 1 Compost+CF 8: % 2 Compost+CF 9: % 4 Compost+CF 10: % 6 Compost+CF

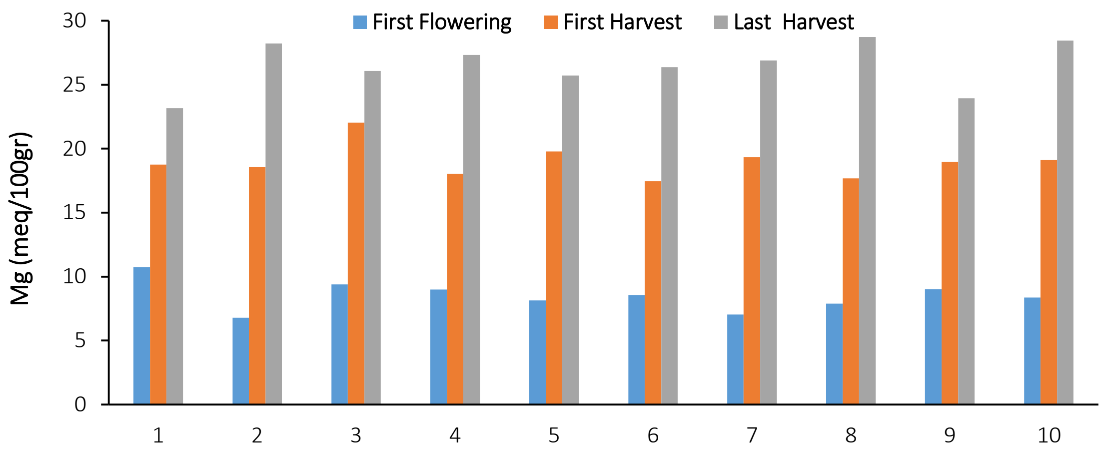
Figure 3. Exchangeable calcium content of soils after the experiment

Exchangeable magnesium (Mg)

Exchangeable Mg results are presented in Figure 4. In your current text, Mg showed limited response at first flowering and first harvest, while Mg was highest at the final harvest stage, with increases across treatments at final harvest. This is consistent with literature indicating that composts can increase exchangeable Mg depending on amendment type and rate. In tomato systems, certain compost amendments have been documented to increase soil exchangeable Mg, alongside K, and these changes may co-occur with improved tomato growth (Su et al., 2022). In greenhouse cultivation, municipal solid waste compost applications have also been reported to increase soil Mg depending on dose (even when statistical significance is limited), aligning with the dose-responsive behavior observed for Mg in some organic-amendment studies (Aydinşakir et al., 2011).

Overall, your results align with the general evidence that compost amendments can increase exchangeable base cations and influence broader fertility indicators (CEC/base saturation), but responses are conditional on compost composition and combined fertilization strategy (Abreu Jr. et al. 2001).

A key practical point for this manuscript is to explicitly address why exchangeable Na increased in several treatments and stages, and to link this to the compost soluble K/Na balance and exchange mechanisms. Mechanistic evidence shows that K in compost can replace Na held on soil exchange sites via both weaker and stronger adsorption domains, but Na reduction is not guaranteed when compost contains high soluble Na (Tong et al., 2021).



1: Control 2: Chemical Fertilizer(CF) 3: % 1 Compost 4: % 2 Compost 5: % 4 Compost 6: % 6 Compost 7: % 1 Compost+CF 8: % 2 Compost+CF 9: % 4 Compost+CF 10: % 6 Compost+CF

Figure 4. Exchangeable magnesium content of soils after the experiment

Conclusion

Tomato residue compost, applied alone or with mineral fertilization, altered soil exchangeable base cations during greenhouse tomato cultivation. Exchangeable K and Mg generally increased with compost application, while exchangeable Ca exhibited stage- and dose-dependent variation. Exchangeable Na tended to be highest at the final harvest stage and frequently increased after treatments, underscoring the necessity of compost quality characterization and soil monitoring when compost is used as a fertility input. The findings support integrated compost–mineral fertilizer strategies for improving soil nutrient status in greenhouse tomato systems, while emphasizing careful attention to Na dynamics and related salinity/sodicity indicators.

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Soil quality assessment in pine dominated forest area using soil management assessment framework

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Abstract

Soil quality assessment is fundamental for ensuring the sustainability of forest ecosystems, particularly in pine-dominated landscapes where unique soil conditions influence ecosystem functioning. This study applied the Soil Management Assessment Framework (SMAF) to evaluate soil quality in pine dominated forest area of the 19 Mayis district, Samsun Province, Türkiye. A total of 72 soil samples were collected across forest lands, and twelve physical, chemical, and biological indicators were analyzed, including bulk density, aggregate stability, available water content, soil organic carbon, pH, nutrient availability, and microbial biomass carbon. Indicator values were transformed into unit less scores using SMAF scoring functions and integrated into a Soil Quality Index (SQI).Results revealed that soils under pine forest exhibited medium overall quality, with SQI values ranging from 42.3 to 75.6 (mean 61.5). Physical properties, particularly bulk density, scored high, indicating favorable soil structure. Biological properties also performed strongly, with microbial biomass and organic matter contributing to high biological scores. In contrast, chemical properties represented the main constraint, as acidity, low phosphorus availability, and variable nutrient status reduced chemical quality scores. Spatial mapping demonstrated heterogeneous soil quality patterns, with high quality zones concentrated in the northern and northwestern parts of the study area, while low-quality soils were more frequent in the south and southeast. These findings highlight that while pine forest soils maintain favorable structure and biological activity, their chemical limitations may restrict long term productivity and ecosystem resilience. Application of SMAF combined with GIS proved effective for diagnosing site-specific soil quality constraints, providing a valuable tool to guide sustainable management, biodiversity conservation, and climate mitigation strategies in pine dominated ecosystems.

Keywords: Soil quality index, SMAF, pine forests, soil properties, nutrient limitations, sustainable management.

Introduction

Soil is a vital element of land based ecosystems, playing a crucial role in supporting plant growth, managing water and nutrient cycles, fostering biodiversity, and mitigating environmental changes (Binkley & Fisher, 2019; Lal, 2020). The idea of soil quality has become an essential framework for understanding how well soils can function within ecosystem and land-use limits. Soil quality is typically defined as the soil's capacity to support biological productivity, uphold environmental quality, and enhance the health of plants and animals

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(Doran & Parkin, 1994; Karlen et al., 2021). Evaluating soil quality is therefore crucial for ensuring the long-term sustainability of ecosystems, especially in sensitive areas like forested regions. Forests, particularly those dominated by coniferous species such as pine, significantly impact soil properties through litter inputs, root activity, and microclimatic regulation (Augusto et al., 2002; Babur et al., 2022). Pine forests are widespread across temperate and boreal zones and serve as key ecosystems for timber production, biodiversity conservation, and carbon storage (Prescott, 2002; Pan et al., 2011; Babur et al., 2025).

However, soils under pine-dominated stands often display distinct characteristics compared to broadleaf forests, such as acidic pH, slower organic matter decomposition, and accumulation of resistant litter components (e.g., lignin-rich needles). These traits can affect soil nutrient availability, microbial activity, and organic matter dynamics, thereby influencing overall soil quality (Prescott, 2002; Binkley & Fisher, 2019; Kavgacı et al., 2025). Additionally, forest management practices, climate change, and land use pressures can modify soil properties in pine-dominated systems, making soil quality assessment a crucial task for ecological monitoring and sustainable management (Bronick & Lal, 2005; Ruiz et al., 2020; MDPI, 2024). Evaluating soil quality necessitates robust tools that integrate multiple soil indicators into a comprehensive index. Traditional assessments often depend on single-parameter measurements, which may not fully capture the multidimensional nature of soil functions (Andrews et al., 2004; Bünemann et al., 2018).

To address this limitation, the Soil Management Assessment Framework (SMAF) has been developed as a standardized and adaptable tool to evaluate soil quality across various ecosystems and management systems. The SMAF is based on selecting a minimum data set of soil indicators including physical, chemical, and biological properties that are scored against threshold values and then integrated into indices representing soil functions such as nutrient cycling, water regulation, and biological activity (Andrews et al., 2004; Idowu et al., 2009; Cherubin et al., 2016). This approach provides a holistic understanding of soil performance and allows for comparisons across land uses, management strategies, and ecological conditions (Karlen et al., 2021).

Applying the SMAF model to forest ecosystems, especially those dominated by pine, proves particularly beneficial. Pine soils often encounter challenges such as acidification, nutrient limitations (notably nitrogen and phosphorus), and slower organic matter turnover, which, if not properly managed, may compromise their long-term functionality (Prescott, 2002; Binkley & Fisher, 2019; Babur et al., 2022). By employing SMAF, researchers and forest managers can gain an objective assessment of soil quality, identifying potential constraints and opportunities for sustainable forest management (Ruiz et al., 2020; Babur et al., 2025). These assessments also support broader ecological goals, including carbon storage, biodiversity conservation, and climate change mitigation (Pan et al., 2011; Lal, 2020; Kavgacı et al., 2025).The ecological significance of pine forests and their unique soil characteristics, using the SMAF model to assess soil quality is a crucial step toward understanding the sustainability of these ecosystems. This study aims to apply the SMAF framework to soils in a pine-dominated forest area in 19 Mayis district, Samsun Turkey with the goal of identifying key soil quality indicators, evaluating the overall soil quality index, and providing insights for sustainable management and conservation practices.

Material and Methods

Study Area

The study was conducted in the pine dominated forests distributed within the boundaries of 19 Mayis district, located in Samsun Province. Samsun Province is situated along the Black Sea coastal zone, between the deltas formed by the Kızılırmak and Yeşilırmak rivers as they flow into the Black Sea (Figure 1). In terms of geographical coordinates, Samsun is located between 40°50' and 41°51' N latitude, and 37°08' and 34°25' E longitude. This region encompasses the Bafra and Çarşamba Plains, which possess high agricultural potential, and hosts the deltas of the Yeşilırmak and Kızılırmak rivers (Dengiz and Sarıoğlu, 2011).

Samsun Province exhibits three fundamental geomorphological characteristics: (1) the mountainous areas located in the southern part of the province, (2) the plateaus situated between the mountainous zones and the coastal strip, and (3) the coastal plains stretching between these plateaus and the Black Sea coast.

Climatically, Samsun Province is generally characterized by a temperate climate. However, there are distinct climatic differences between the coastal zones and the inland areas. Along the coastal strip, the province is under the influence of the Black Sea climate, where summers are typically hot and humid, while winters are mild and rainy. In contrast, the inland areas display features more in to a continental climate, with hot and dry summers and cold winters exhibiting continental transitions.

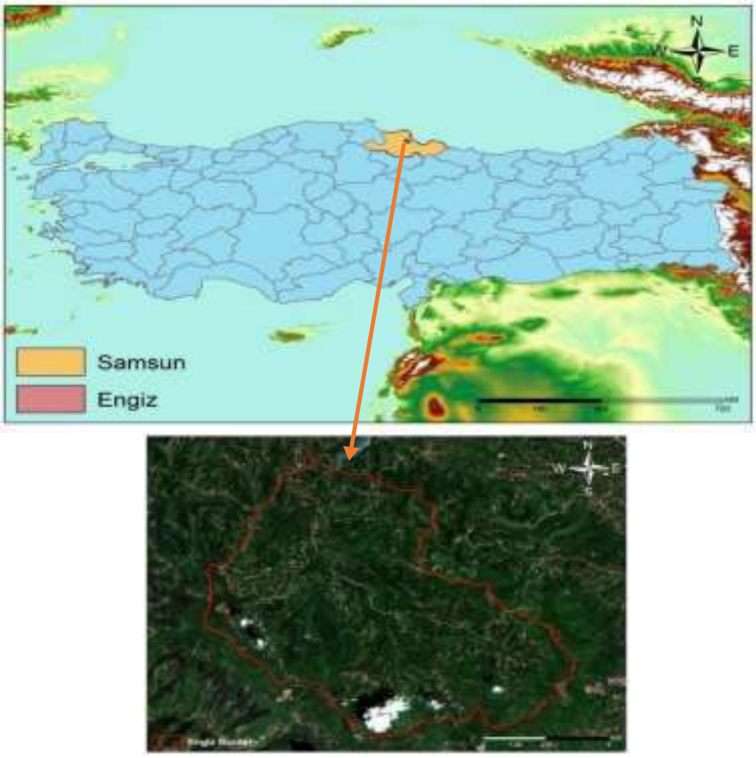

Figure 1.Study Loction Map

In terms of mean annual temperature in the coastal regions of Samsun, data recorded from meteorological stations in Bafra and Atakum districts indicate averages ranging between 13 and 15 °C. According to long-term averages, the lowest temperature was recorded in March, with a mean of 7.5 °C, while the highest was observed in August, with a mean of 23.6 °C. Precipitation data from Bafra and Atakum reveal an average annual total ranging between 700 and 800 mm. Within the scope of this study, long-term mean precipitation and temperature data obtained from meteorological stations in Atakum (1962–2016) and Bafra (1963–2016) were utilized (Table 1).

Table 1. Long-term mean precipitation and temperature data obtained from meteorological stations

	Station			
	Atakum		Bafra	
Months	Precipitation mm	Temp°C	Precipitation mm	Temp °C
January	64.9	7.1	78.2	5.8
Feb	53.3	7.1	56.2	6.2
March	61.5	8.1	56.5	7.5
April	58.7	11.4	52.3	11.1
May	51.5	15.7	42.8	15.5
June	48.1	20.4	41.6	20.2
July	33.1	23.3	27.6	22.9
August	40.8	23.6	41.1	22.8
September	51.5	20.1	54.2	19.3
October	82.4	16.1	87.8	15.2
November	82.7	12.4	85.5	11.4
December	81.5	9.3	93.7	7.9
Year	710.0	14.6	717.5	13.8

Soil Sampling and Analysis

Using ArcGIS software, 72 sampling points were spread randomly throughout the study region. A total of 72 surface soil samples (0–30 cm), both disturbed and undisturbed, were collected, air-dried, crushed, and sieved to 2 mm for laboratory analysis. Fresh samples were reserved specifically for biological assessments.

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 2.

Table 2. 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 Analysis

The Soil Management Assessment Framework (SMAF) was applied to evaluate soil quality in the pine-dominated forest study area. The SMAF methodology consists of three main phases: (i) selection of soil quality indicators, (ii) interpretation of measured values using nonlinear scoring functions, and (iii) integration of scores into a single Soil Quality Index (SQI) (Andrews et al., 2004).

A total of twelve soil indicators were selected to represent physical, chemical, and biological properties. Physical indicators included available water content, water-filled pore volume, bulk density, and aggregate stability. Chemical indicators included soil organic carbon, pH, electrical conductivity, sodium adsorption ratio, plant-available phosphorus, potential mineralizable nitrogen and plant-available potassium. Biological indicators consisted of microbial biomass carbon. This minimum dataset was chosen to reflect key soil functions such as water retention, nutrient availability, and microbial activity in pine forest soils.

Measured values of each indicator were transformed into unit less scores ranging from 0 to 1 using SMAF scoring functions. Three types of scoring curves were applied: "more is better," "less is better," and "optimum," depending on the ecological role of each indicator Figure 2. (Karlen & Stott, 1994; Pacci, Kaya, Dengiz, & Turan, 2021). For example, higher values of soil organic carbon received higher scores ("more is better"), while lower values of bulk density were favored ("less is better"), and intermediate values of soil pH were considered optimal ("optimum") (Wijekoon et al.,2024).

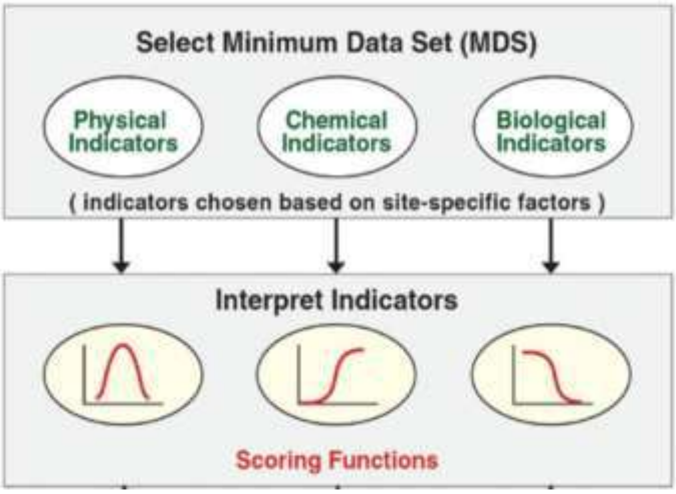

Figure 2.Indicator interpretation (Andrews & Carroll, 2001)

The overall soil quality index (SQI) was calculated using the additive index method, where the sum of all indicator scores was divided by the total number of indicators, and the result was multiplied by 100 (Pacci et al., 2021). The formula used was,

$$SQI = \left(\frac{\sum^{n} Xi}{n}\right) \times 100$$

Where SQI is the Soil Quality Index, "Xi" is the score of the "ith" indicator, and "n" is the total number of indicators. Soil quality was classified into five categories: very low (< 40), low (40–55), medium (55–70), high (70–85), and very high (> 85), following the approach of Idowu et al. (2009).

Descriptive statistics, including minimum, maximum, mean, standard deviation, coefficient of variation, skewness, and kurtosis, were calculated using Minitab 17 software to assess variability of soil properties. Spatial distribution of soil quality was mapped using ArcGIS 10.5, applying the Inverse Distance Weighting (IDW) interpolation method with power 2. The resulting maps allowed for visualization of SQI variability across the pine forest landscape and facilitated interpretation of soil quality in relation to site conditions.

Results and Discussion

The descriptive statistics indicated that soil properties in the pine-dominated forest varied considerably (Table 3). Soil pH ranged from 4.34 to 7.59 with a mean of 5.33, reflecting generally acidic conditions often observed under coniferous cover due to slow litter decomposition and organic acid release (Augusto et al., 2002). Electrical conductivity was low (mean 0.16 dS m^{-1}), suggesting minimal salinity concerns. Organic carbon content averaged 6.17% with high variability (CV 41.9%), while total nitrogen was low (mean 0.23%), consistent with the typically N-limited status of pine forest soils (Binkley & Fisher, 2019). Available phosphorus was also low (mean 6.79 mg kg^{-1}) and showed very high variability (CV 85.0%), indicating nutrient limitation that is common in coniferous ecosystems (Prescott, 2002). Potassium ranged widely (23.6–430.6 mg kg^{-1}), with a high coefficient of variation (80.9%). Bulk density averaged 1.17 g cm^{-3}, within acceptable limits for forest soils (Arshad et al., 1996), while available water content was relatively low (mean 0.12 cm^3 cm^{-3}). Microbial biomass carbon varied considerably (0.83–34.7 mg g^{-1}; CV 53.2%), reflecting spatial heterogeneity in microbial activity, which is strongly influenced by organic matter distribution (Insam, 1990).

The soil quality scores derived from SMAF highlighted these trends. The physical quality score ranged from 47.0 to 70.5, with a mean of 60.3 (CV 8.3%), placing it in the medium category. The chemical quality score showed greater variability (range 23.2–73.9, mean 48.3, CV 17.0%) and was classified as low, reflecting the effects of acidity and nutrient limitations. In contrast, the biological quality score was relatively high, ranging from 51.6 to 93.6 with a mean of 75.8 (CV 14.1%), suggesting strong microbial activity supported by organic matter inputs. The integrated Soil Quality Index (SQI) varied between 42.3 and 75.6, with an average of 61.5 (CV 9.1%), placing the soils in the medium category according to Idowu et al. (2009). These results suggest that while the soils maintain favorable physical and biological functioning, chemical constraints particularly acidity, low phosphorus, and variable nutrient availability reduce overall soil quality and may limit long term ecosystem productivity.

Variable	Mean	StDev	Variance	CoefVar	Minimum	Maximum	Skewness	Kurtosis
EC (dS/m)	0.1604	0.1314	0.0173	81.92	0.0101	0.6267	2	4.51
pH	5.3305	0.6924	0.4794	12.99	4.34	7.59	0.91	0.76
%OC	6.173	2.586	6.688	41.89	0.318	14.474	0.64	1.09
%Clay	23.84	9.95	98.93	41.72	5.05	47.74	0.55	-0.2
%Silt	26.492	8.049	64.793	30.38	3.694	47.121	-0.14	0.39
%Sand	49.67	13.6	185.04	27.39	13.72	77.15	0.11	-0.3
BD (g/cm^3)	1.1685	0.1134	0.0129	9.7	0.86	1.6	0.82	2.25
Avail. water	0.11973	0.02014	0.00041	16.82	0.07	0.16	-0.48	0.01
%N	0.2283	0.0878	0.0077	38.44	0.0648	0.5011	0.43	0.93
%AS	58.34	11.67	136.14	20	29.55	84.75	0	0.06
P ppm	6.791	5.773	33.333	85.02	0.942	32.858	2.04	5.49
mgMBC/gsoil/24h	15.959	8.496	72.187	53.24	0.83	34.685	0.51	-0.63
SAR	0.3008	0.3746	0.1403	124.52	0.0256	2.575	5.32	29.43
K ppm	94.7	76.68	5879.56	80.97	23.6	430.62	2.59	8.25
Physical Quality Score	60.273	4.995	24.947	8.29	46.978	70.538	-0.7	0.21
Chemical Quality Score	48.33	8.206	67.332	16.98	23.177	73.932	0.21	0.82
Biological quality Score	75.83	10.68	114.12	14.09	51.64	93.55	-0.08	-0.85
SQI	61.479	5.59	31.248	9.09	42.274	75.554	-0.35	1.23

The SMAF analysis revealed contrasting patterns among soil quality indicators in the pine-dominated forest (Figure 3). Physical properties showed mixed performance such as bulk density scored very high (92), suggesting favorable soil structure, while aggregate stability (46), available water content (53), and water-filled pore space (50) were all in the low category, indicating potential structural limitations for water retention. Chemical properties presented the greatest constraints, with soil pH (17), electrical conductivity (0), plant-available phosphorus (40), and sodium adsorption ratio (24) all in the very low category. These findings confirm the chemical vulnerability of pine forest soils, where acidity and nutrient limitations are common (Augusto et al., 2002; Prescott, 2002). In contrast, total nitrogen (99) and organic carbon (99) scored very high, reflecting the accumulation of organic matter inputs from pine litter. Potassium availability was moderate (59), while biological indicators performed better, with microbial biomass carbon scoring high (75), suggesting active microbial processes supported by organic inputs. The integrated soil quality index (SQI) was 61, placing the soils in the medium category (Idowu et al., 2009). Overall, these results indicate that while forest soils maintain strong biological activity and favorable bulk density, chemical constraints particularly acidity and phosphorus deficiency remain the primary limitations to soil quality in pine-dominated systems (Binkley and Fisher, 2019).

SOIL QUALITY RESULTS

	INDICATOR	SCORE	QUALITY SCORE	QUALITY ASESSMENT
PHYSICAL	Aggregrate stability	0.460	46	LOW
	Available water content	0.525	53	LOW
	Bulk density	0.923	92	VERY HIGH
	Water filled pore space	0.502	50	LOW
CHEMICAL	Soil pH	0.169	17	VERY LOW
	Electrical conductivity	0.004	0	VERY LOW
	Plant available Phosphours	0.398	40	VERY LOW
	Total Nitrogen	0.997	99	VEY HIGH
	Organic Carbon	0.987	99	VERY HIGH
	Sodium Adsorption Ratio	0.241	24	VERY LOW
	Soil test Potassium	0.592	59	MEDIUM
BIOLOGICAL	Microbial Biomass Carbon	0.745	75	HIGH
	Land Quality		61	MEDIUM

Figure 3.SMAF Analysis Soil Quality Results

The spatial distribution of soil quality in the pine dominated forest area, derived from the SMAF- based Soil Quality Index (SQI) and showed considerable variability (Figure 4). SQI values ranged from 42.0 to 75.9, classifying soils from low to high quality. The map indicates that large portions of the study area fall within the medium category, while localized patches of both high-quality (green areas) mainly concentrated in the northern and northwestern sections and low-quality soils common in the southern and southeastern parts (red areas) are dispersed across the landscape. These patterns reflect the heterogeneous nature of forest soils, where variations in topography, organic matter accumulation, and microclimatic conditions influence soil properties (Bronick & Lal, 2005; Cambardella et al., 2004).

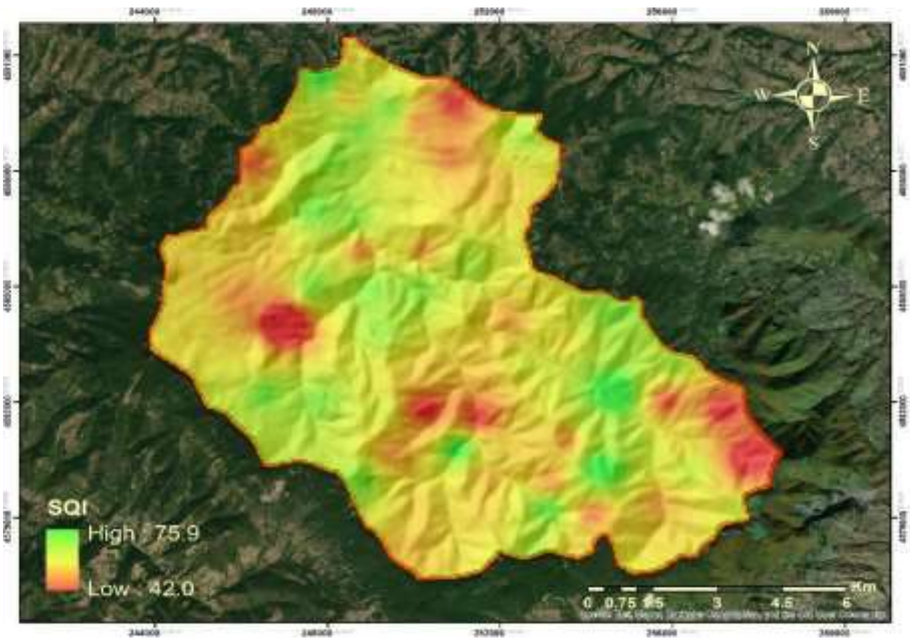

Figure 4. Soil quality distribution map of the study area

The presence of higher SQI values in some locations suggests favorable conditions for soil biological activity and organic matter content, consistent with the high scores observed for total nitrogen, organic carbon, and microbial biomass carbon. Conversely, the low SQI patches align with chemical limitations identified in the SMAF analysis, particularly soil acidity and low phosphorus availability, which are common in pine ecosystems (Augusto et al., 2002; Prescott, 2002). The spatial heterogeneity revealed by the map underscores the importance of site specific soil management strategies, as uniform management approaches may not address localized constraints effectively. Incorporating spatially explicit soil quality assessments such as SMAF combined with GIS therefore provides a more robust basis for sustainable forest management (Pacci, Kaya, Dengiz, & Turan, 2021).

This study successfully applied the SMAF model to provide a comprehensive and quantitative assessment of soil quality in a pine dominated forest. The results highlight that while these soils possess strengths in physical structure and biological activity, they are fundamentally constrained by chemical limitations, including low pH and nutrient deficiencies, which are typical of coniferous ecosystems. The integrated Soil Quality Index (SQI) revealed that the soils are of medium quality, but the high spatial variability emphasizes that soil quality is not uniform across the landscape. The localized patches of low SQI soil underscore the need for targeted, site-specific management interventions rather than broad scale approaches. For example, strategies aimed at mitigating acidification or enhancing nutrient availability could significantly improve overall soil quality in these constrained areas. By demonstrating the utility of the SMAF-GIS integration, this research offers a robust framework for ecological monitoring and provides a scientific basis for developing sustainable forest management and conservation strategies that address the unique challenges of pine dominated forest soils.

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Changes In Nutrient Availability and Microbial Activity In Acidic Soil Treated With Microbial Inoculants and Alkaline Input

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Abstract

Soil acidity limits nutrient availability and microbial activity, directly affecting crop productivity. This study evaluated the effects of microbial inoculation with Bacillus megaterium var. phosphaticum RK1 and alkaline amendments (KOH and K_2SiO_3) on the chemical and microbial properties of acidic soil cultivated with wheat (Triticum aestivum L.). A greenhouse experiment was conducted using a completely randomized design (CRD) with 10 treatment combinations and 3 replications. Key indicators including soil pH, electrical conductivity (EC), total nitrogen (N), organic matter (OM), available phosphorus (P), microbial biomass carbon (MBC), and soil basal respiration (SBR) were measured to assess the treatment effects.

Alkaline amendments significantly increased soil pH from 5.7 (control) to 6.63 in the KOH (F) + BM treatment ($p < 0.05$). EC rose from 0.80 to 1.32 dS/m ($p < 0.05$), reflecting improved ionic concentration. Total nitrogen showed a modest increase under combined treatments, while microbial inoculation alone had no significant effect. Organic matter content remained statistically unchanged across all treatments. Available phosphorus improved substantially, with Bray I P increasing from 4.85 ppm in the control to 8.66 ppm in K_2SiO_3 (F) + BM ($p < 0.05$). MBC rose from 13.98 mg/g to 29.52 mg/g, and SBR increased from 0.070 to 0.121 g CO_2/g soil/24h ($p < 0.05$ for both), indicating enhanced microbial abundance and activity.

These results demonstrate that the combined application of phosphate-solubilizing bacteria and potassium-based alkaline amendments, particularly half-dose K_2SiO_3 + BM, effectively enhances phosphorus availability and microbial activity ($p < 0.05$). The findings support an integrated biochemical approach as a sustainable solution for improving acidic soils.

Keywords: Acidic soil, Bacillus megaterium, Phosphorus solubilization, Soil fertility restoration, Soil biological activity

Introduction

Acidic soils are common across many region of the world. These are the soil with pH below 7, and when it drops below 6, they often hinder plant growth and development. The problem is that acidic soil tends to be saturated with hydrogen (H^+), aluminum (Al^{3+}), and iron (Fe^{3+}) ions which bind with essential nutrients and make it unavailable to plants. The high reactivity of these ions creats the hostile conditions for plants roots and soil microorganism resulting poor nutrient availability and reduced biological activity in soils.

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To maintain the yields in such soils farmers often depends on the application of external inputes including mineral fertilizers and liming materials. However, fertilizers use effenciency of acidic soil is typically low, and prolonged dependency of synthetic fertilizers has contributed to further soil degradatioan and environmental issue such as eutrophication. As a result, alternative strategies are being explored to improve both soil chemical balance and biological health. Potassium-based alkaline amendments are getting attention such as potassium hydroxide (KOH) and potassium silicate (K_2SiO_3) . These compounds not only neutralize soil acidity but also contribute essential nutrients KOH supplies potassium, while K_2SiO_3 adds silicon, which has been linked to enhanced stress resistance and improved plant-microbe interactions. They may also play role in nutrient solubility, reduce aluminum toxicity, and improve cation exchange conditions in the rhizosphere.

On the biological side, low soil pH is known to suppress microbial growth and enzyme activity, disrupting nutrient cycling and organic matter decomposition. Such soil can be inoculated with plant-beneficial microbes such as phosphate-solubilizing bacteria (PSB) which might help to restore microbial function and improve nutrient mobilization. Bacillus megaterium is known for its ability to release organic acids, solubilize nutrients, and stimulate microbial respiration and enzyme activity. Bacillus megaterium takes parts in improve both nutrient access and overall soil functioning.

While individual use of alkaline amendments or microbial inoculants has shown potential in managing acidic soils, their combined effect remains underexplored. Previous studies have often focused narrowly on phosphorus availability or soil pH, without fully addressing microbial responses or overall biochemical changes. There is a need to evaluate how microbial inoculation and potassium-based chemical treatments interact to influence soil chemical and biological dynamics holistically.In this study we are investigating the combined effects of Bacillus megaterium var. phosphaticum RK1 with two alkaline amendments, KOH and K_2SiO_3, on soil pH, nutrient dynamics, and microbial activity in acidic soils, using wheat (Triticum aestivum L.) as the test crop. It addresses the broader challenge of managing multiple soil constraints under acidic conditions, including chemical imbalances, microbial inactivity, and low nutrient availability. For this study, we hypothesized that: (i) that alkaline amendments improve soil chemical properties by raising pH and enhancing ionic balance, and (ii) that microbial inoculation boosts microbial activity and supports nutrient mobilization. The core objective is to compare the individual and combined effects of microbial and chemical treatments on key soil quality indicators.

Material and Methods

Soil sampling site and characteristics

Soil was collected from a hazelnut orchard in Boztekke village, Giresun Province, Turkey (UTM zone 37T: 4524850–4524895 N, 461870–461915 E; 228 m elevation). The region has a humid Black Sea climate with an average annual temperature of 9 °C.The collected soil was air-dried, crushed, sieved (4 mm), and stored for further use. The soil was clay in texture with a slightly acidic pH of 5.75. Electrical conductivity (0.935 dS/m) indicated moderate salinity, and organic carbon content (2.17%) reflected a fair level of organic matter. Available nitrogen (0.172%) and phosphorus (5.12 ppm) were low, pointing to potential nutrient deficiencies. The cation exchange capacity was adequate, with calcium (28.62 me/100g) and magnesium (21.82 me/100g) being the dominant nutrients. Lime content (0.82% $CaCO3$) was also recorded.

Experimental design

This greenhouse experiment was set up using a Completely Randomized Design (CRD) with a factorial arrangement to evaluate the interactive effects of microbial inoculation and alkaline amendments on acidic soil. A total of ten treatments were designed, combining Bacillus megaterium var. phosphaticum RK1 with two alkaline materials- potassium silicate (K_2SiO_3) and potassium hydroxide (KOH) applied at both full and half doses. Each treatment was replicated three times, resulting in a total of 30 experimental pots.

Before the main experiment, a preliminary dose optimization was carried out to determine effective amendment levels capable of adjusting soil pH from its initial acidic range (pH 5.75) to a range favorable for wheat growth (approximately 6.5-7.0). Based on these trials, the full dose for potassium hydroxide was determined to be 4 mL KOH mixed with 16 mL distilled water, while the full dose for potassium silicate was 0.4 mL mixed with 19.6 mL distilled water.

The ten treatments were as follows: T1: Untreated control, T2: Bacillus megaterium var. phosphaticum RK1 only, T3: Full dose of potassium silicate, T4: full dose of potassium hydroxide, T5: Half dose of potassium silicate, T6: Half dose of potassium hydroxide, T7: Full dose potassium silicate + Bacillus megaterium var. phosphaticum RK1, T8: Full dose potassium hydroxide + Bacillus megaterium var. phosphaticum RK1, T9: Half dose potassium silicate + Bacillus megaterium var. phosphaticum RK1, and T10: Half dose potassium hydroxide + Bacillus megaterium var. phosphaticum RK1. Each 20 cm diameter pot was filled with 2.89 kg of oven-dried soil. No external fertilizer was applied to any treatment.

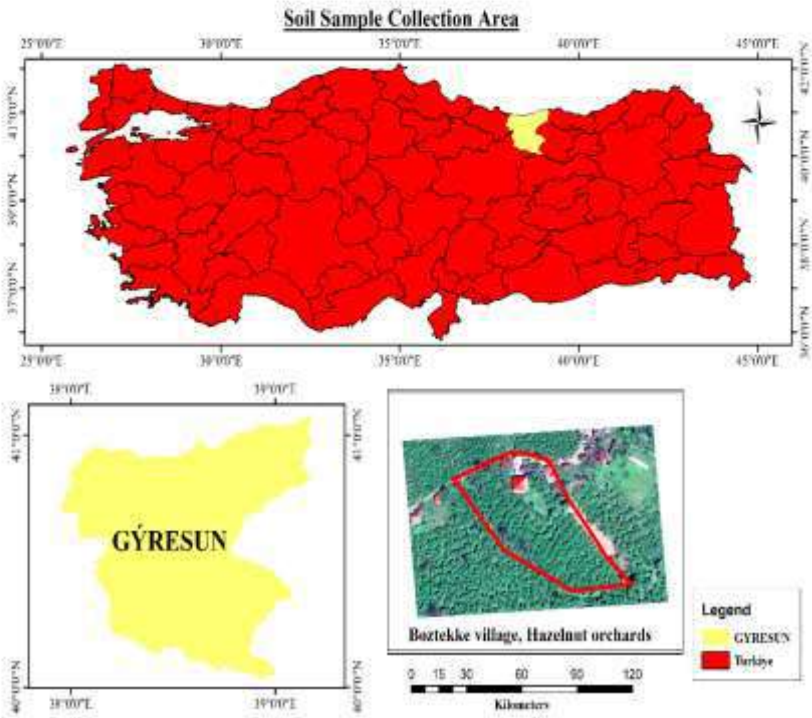

Figure 1. Soil sample collected area

Planting and bacterial inoculation

Surface-sterilized wheat seeds (Triticum aestivum L.) were sown in each pot, with 22 seeds per pot initially, later thinned to 17 uniform seedlings after germination. For treatments involving microbial inoculation, 10 mL of a Bacillus megaterium var. phosphaticum RK1RK1 suspension (10^8 CFU/mL) was applied directly into the seed zone at the time of sowing. Soil moisture was maintained at field capacity through daily weighing and watering to ensure consistent hydration across all pots.The bacterial inoculum, Bacillus megaterium var. phosphaticum RK1, was obtained from the Soil Microbiology Laboratory at Ondokuz Mayıs University. It was cultured in a liquid broth medium containing peptone, meat extract, and manganese sulfate ($MnSO_4$), with the pH adjusted to 7.0. The culture was prepared under aseptic conditions before application.

Soil physicochemical and biological analysis

Soil pH and electrical conductivity (EC) were determined using a 1:1 soil-to-water suspension based on the method by Rhoades (1996). Organic matter was measured using the Walkley-Black dichromate oxidation method, and total nitrogen content was analyzed through the Kjeldahl digestion procedure. Available phosphorus was extracted using the Bray I method, suitable for acidic soils, and quantified colorimetrically using ammonium molybdate and stannous chloride. Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) were extracted with ammonium acetate and analyzed by atomic absorption or flame photometry. Microbial Biomass Carbon (MBC) was measured using the Substrate-Induced Respiration (SIR) method following Anderson and Domsch (1978). In this method, 6 g of moist soil was amended with 1 mL of 1% glucose solution, incubated in airtight flasks at 22–25 °C for 24 hours. The CO_2 released was trapped in 10 mL of 0.05 N NaOH, precipitated with $BaCl_2$, and the remaining NaOH was titrated with 0.05 N HCl. The amount of CO_2-C evolved served as an estimate of microbial biomass. Basal Respiration (BR) was assessed similarly, without glucose addition, to capture native microbial activity. CO_2 evolution was recorded and expressed as CO_2-C released per gram of soil over 24 hours.

Results and Dıscussıon

Soil pH and electrical conductivity (EC)

In our greenhouse experiment, soil pH and electrical conductivity (EC) were significantly affected by treatments ($p < 0.05$), but bacterial inoculation on its own and its interaction with amendments had no significant effect. This result was consistent with previous work showing that *Bacillus megaterium var.*

phosphaticum combined with rock phosphate can influence soil properties but bacterial inoculation on its own and its interaction with amendments had no significant on pH (Bayraklı, 2022). The control treatments, with or without bacterial strain, recorded the lowest pH values (5.75 and 5.70), reflecting the persistence of soil acidity when left untreated. Among the alkaline amendments, the highest pH was recorded in the full-dose KOH treatment with bacterial inoculation (6.63), followed by KOH full dose alone (6.57) and K_2SiO_3 full dose with bacterial inoculation (6.48). The pH increase is likely due to the neutralization of H^+ ions and the addition of base-forming cations such as K^+ and OH^-, consistent with previous studies showing that alkaline amendments raise soil pH by replacing exchangeable acidity with basic cations and precipitating Al^{3+} as non-toxic hydroxides (Haynes and Naidu, 1998; Hussain et al. 2019). KOH showed the strongest liming effect, likely due to its high solubility and rapid release of hydroxide ions (Mokolobate and Haynes, 2002).

Electrical conductivity (EC) was also significantly influenced by alkaline amendments and the presence of *Bacillus megaterium var. phosphaticum RK1*, although the interaction between the two was not significant. The rise in EC reflects the release of soluble ions such as K^+, OH^-, and silicate species derived into the soil solution, with KOH based treatments producing greater increases than silicate-based treatments due to the higher solubility and ionic strength of KOH (Bolan et al., 2003; Obour et al., 2017).

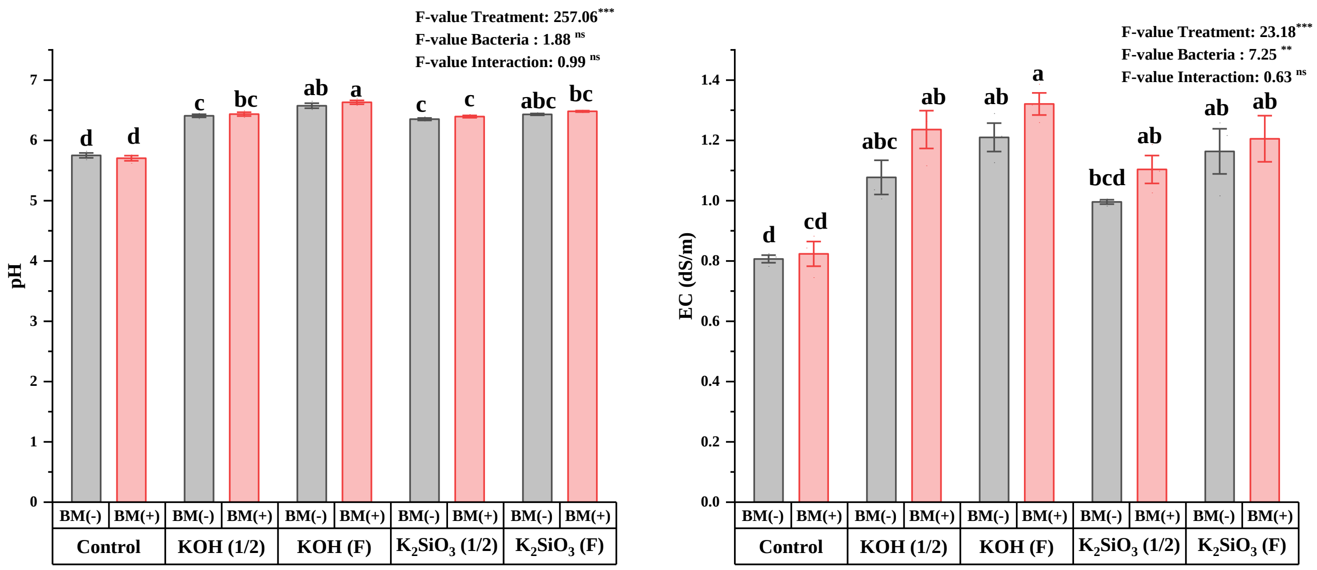

Figure 2. Combined effects of Bacillus megaterium var. phosphaticum RK1 and Alkaline amendments on soil pH and EC (dS/m) content of soil.

Inoculated treatments tended to have slightly higher EC values than their non inoculated counterparts, suggesting that *Bacillus megaterium var. phosphaticum RK1* may have enhanced nutrient solubilization through organic acid production, phosphatase activity, or mineral dissolution (Sharma et al., 2013; Alori et al., 2017; Panhwar et al., 2011). This is consistent with previous findings that phosphate-solubilizing bacteria can increase the ionic concentration of the soil solution by mobilizing bound nutrients and releasing anions and cations into plant-available forms (Khan et al., 2009). Overall, these results support the view that while alkaline amendments primarily drive pH changes, microbial inoculants contribute to increased EC by stimulating nutrient turnover, and their combined application offers complementary benefits for improving soil chemical properties in acidic soils.

Soil organic matter (OM)

Soil organic matter (OM) content was not significantly affected by bacterial inoculation, alkaline amendments, or their interaction ($p > 0.05$). OM values across treatments remained within a narrow range of approximately 3.5–4.1%, with no statistically distinct differences among treatments. A slight upward trend was observed in plots where *Bacillus megaterium var. phosphaticum* RK1 was applied, particularly in combination with either KOH or K_2SiO_3. This minor increase may be linked to short-term contributions from microbial biomass turnover or enhanced root growth stimulated by microbial inoculation. Increased microbial activity can promote rhizodeposition through root exudation, thereby supplying labile carbon that contributes to the soil organic matter pool (Kuzyakov and Domanski, 2000; Lehmann and Kleber, 2015). However, given the short duration of this experiment, large changes in OM were unlikely. Organic matter accumulation is typically a slow process requiring continuous plant residue inputs, microbial processing, and stabilization through interactions with soil minerals (Cotrufo et al., 2013; Schmidt et al., 2011). The lack of a significant OM response is consistent with previous studies showing that measurable increases in SOM often occur only after long-term management practices such as cover cropping, organic amendment application, or reduced tillage (Powlson et al., 2011). Since neither KOH nor K_2SiO_3 directly supply organic carbon, any observed changes are more likely an indirect effect of enhanced microbial and root activity rather than a direct chemical contribution. Overall, the results suggest that while biological and chemical amendments may stimulate short-term soil biological activity, substantial increases in SOM require sustained organic matter inputs and stable environmental conditions over the long term.

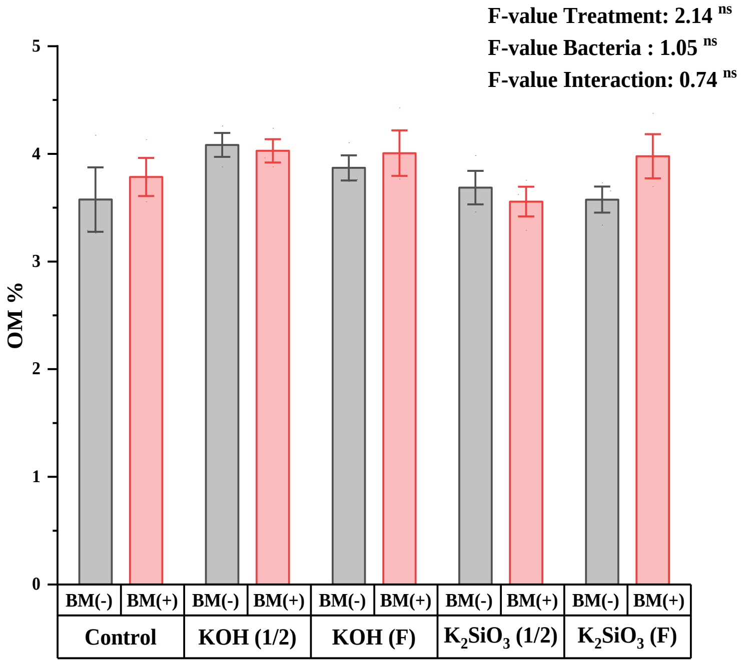

Figure 3. Combined effects of Bacillus megaterium var. phosphaticum RK1 and alkaline amendments on organic Matter content of soil

Total nitrogen (N %)

Total nitrogen content was significantly influenced by both *Bacillus megaterium var. phosphaticum* RK1 inoculation and alkaline amendments ($p < 0.05$), with significant interaction between the two factors. In control treatments, with or without *Bacillus megaterium var. phosphaticum* RK1 inoculation, total nitrogen remained largely unchanged, indicating that microbial inoculation alone was insufficient to alter nitrogen dynamics under acidic conditions. This limited effect is consistent with the suppressive influence of low pH on microbial activity, organic matter decomposition, and nitrogen mineralization (Rousk et al., 2010; Fierer and Jackson, 2006). Acidic conditions can reduce nitrification rates, limit ammonium oxidation, and suppress the growth of nitrogen-transforming microbial populations (Nicol et al., 2008).

When alkaline amendments were applied, particularly in combination with *Bacillus megaterium var. phosphaticum* RK1, total nitrogen levels increased significantly. The highest nitrogen concentration (0.219%) was observed in the half-dose K_2SiO_3 + BM treatment, followed closely by the full-dose KOH + BM treatment. These results suggest a synergistic effect between improved soil pH and microbial activity, where liming agents reduce proton toxicity, increase nutrient availability, and enhance microbial-mediated nitrogen transformations (Haynes and Naidu, 1998; Aciego Pietri and Brookes, 2008). The presence of silicon from K_2SiO_3 may have further supported plant-microbe interactions, root development, and rhizosphere nitrogen cycling through indirect physiological benefits (Liang et al., 2015; Luyckx et al., 2017). The half-dose K_2SiO_3 + BM treatment outperformed its full-dose equivalent, suggesting that moderate alkalinity may provide more favorable conditions for microbial performance than excessive pH shifts. High alkalinity can sometimes create ionic imbalances or induce osmotic stress, which may counteract the benefits of pH correction (Lauber et al., 2008).

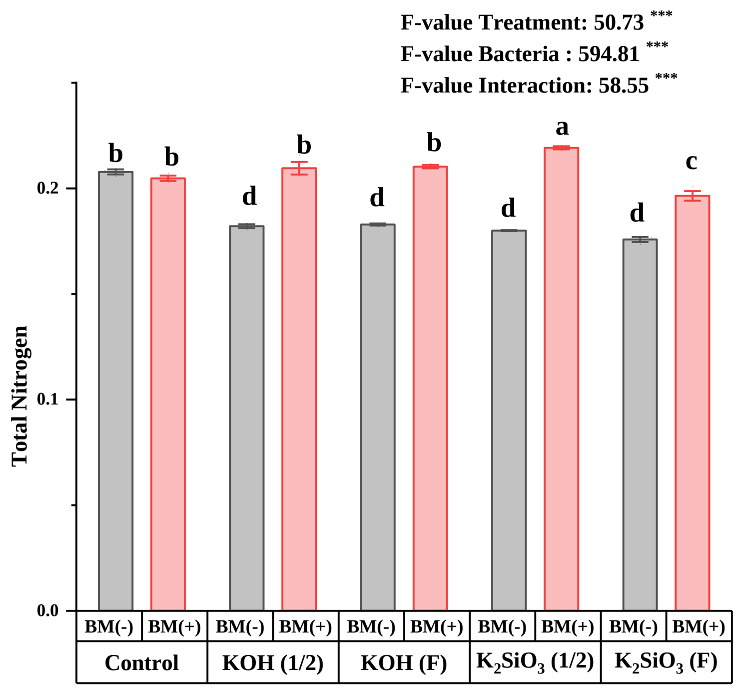

Figure 4. Combined effects of Bacillus megaterium var. phosphaticum RK1 and alkaline amendments on total nitrogen content of soil

Overall, while *Bacillus megaterium var. phosphaticum* RK1 alone had minimal impact in acidic soils, its effects were markedly amplified when paired with suitable alkaline amendments, highlighting the value of integrated microbial and chemical management for improving nitrogen status in acid-affected soils.

Available phosphorus (P)

Bray I extractable phosphorus was significantly affected by treatments, bacterial inoculation, and their interaction ($p < 0.05$), indicating that both chemical and biological inputs contributed to increasing phosphorus availability in the acidic soil. The lowest P values were recorded in the control treatments, regardless of *Bacillus megaterium var. phosphaticum* RK1 inoculation, suggesting that without amendments, acidic conditions promoted strong P fixation through binding with Fe^{3+} and Al^{3+} ions (Hinsinger, 2001; Shen et al., 2011). Inoculation alone was insufficient to overcome this limitation, highlighting the constraint imposed by low pH on microbial solubilization efficiency. The introduction of alkaline amendments increased available P, with the greatest improvements observed when they were combined with *Bacillus megaterium var. phosphaticum* RK1. The highest P content was measured in the full-dose K_2SiO_3 plus BM treatment (8.66 ppm), followed by half-dose K_2SiO_3 plus BM (8.32 ppm) and full-dose KOH plus BM (7.89 ppm). These increases can be explained by two complementary mechanisms. First, the liming effect of KOH and K_2SiO_3 elevated soil pH, reducing Al and Fe bound P and increasing its solubility (Haynes, 1982; Bolan et al., 2003). Second, *Bacillus megaterium var. phosphaticum* RK1 likely enhanced P release through the secretion of organic acids and phosphatases, which chelate metal cations and solubilize mineral-bound phosphorus (Sharma et al., 2013; Alori et al., 2017). Silicon supplied by K_2SiO_3 may have provided an additional benefit. Silicon has been reported to improve root architecture, enhance plant resistance to stress, and indirectly stimulate rhizosphere microbial communities that participate in nutrient cycling (Liang et al., 2015; Luyckx et al., 2017). Notably, the half-dose K_2SiO_3 with BM outperformed several full-dose treatments, indicating that strategic balancing of inputs can be more effective than simply increasing amendment rates.

These findings reinforce the concept that improving P availability in acidic soils requires a combined approach, raising pH to reduce fixation and deploying P-solubilizing microorganisms to mobilize mineral-bound P. The observed synergy between K_2SiO_3 and *Bacillus megaterium var. phosphaticum* RK1 provides strong evidence for integrated soil fertility management in phosphorus-limited acidic environments.

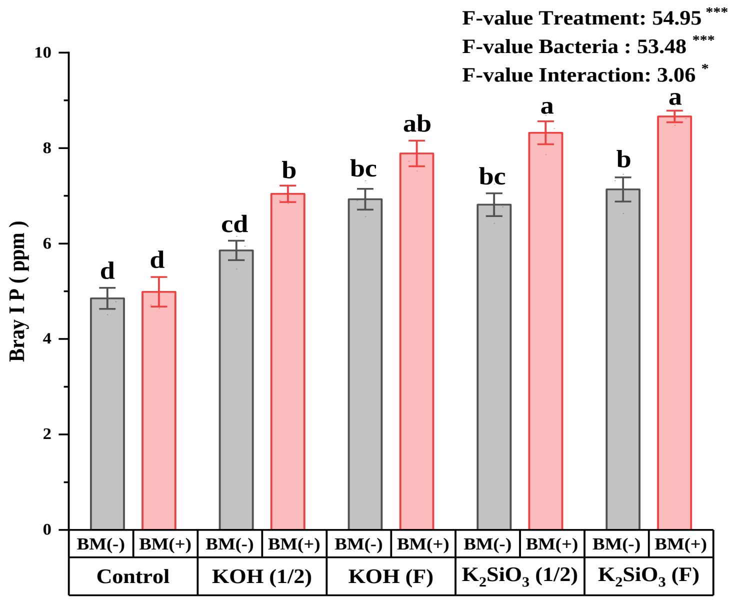

Figure 5. Combined effects of Bacillus megaterium var. phosphaticum RK1 and alkaline amendments on Bray I P content of soil

Microbial biomass carbon (MBC) and Soil basal respiration (SBR)

Microbial biomass carbon (MBC) and soil basal respiration (SBR) are key indicators of soil biological activity, reflecting both the abundance and metabolic activity of microbial communities (Anderson and Domsch, 1993; Wardle, 1992). Both parameters were significantly influenced by *Bacillus megaterium var. phosphaticum* RK1 and alkaline amendments ($p < 0.05$). The lowest values occurred in the untreated control without inoculation, where MBC was 13.99 mg/g and SBR was 0.070 CO_2 g/g, indicating that acidic conditions restricted microbial growth and metabolic function. Even with B. megaterium inoculation alone, increases were minor, suggesting that low pH continued to impose strong constraints on microbial activity. Application of alkaline amendments improved both MBC and SBR across treatments, with the largest increases observed when *Bacillus megaterium var. phosphaticum* RK1 was combined with half doses of either KOH or K_2SiO_3. MBC reached 27.16 mg/g in the KOH (½) + BM treatment and 28.10 mg/g in the K_2SiO_3 (½) + BM treatment, while corresponding SBR values were 0.108 and 0.121 CO_2 g/g, respectively. The improvements likely stem from pH correction, which reduces aluminum and manganese toxicity, enhances nutrient availability, and creates a more favorable environment for microbial proliferation and enzymatic activity (Rousk et al., 2010; Aciego Pietri and Brookes, 2008). Interestingly, full-dose applications of both KOH and K_2SiO_3 also increased microbial activity but did not consistently outperform the half-dose treatments. For example, MBC in KOH (F) + BM was 29.52 mg/g and SBR was 0.119 CO_2 g/g, while K_2SiO_3 (F) + BM showed slightly lower values of 25.20 mg/g for MBC and 0.101 CO_2 g/g for SBR. This pattern suggests that excessively high alkalinity may cause ionic imbalances or osmotic stress, which can limit microbial activity despite improved pH (Bünemann et al., 2018; Lauber et al., 2008).

Table 1 Effect of Bacillus megaterium var. phosphaticum RK1 and alkaline amendments on microbial biomass carbon (MBC) and soil basal respiration (SBR) in acidic soil

	MBC (mg MBC/g Soil/24h)		SBR (CO_2/g soil/24h)	
Treatments	BM (-)	BM (+)	BM (-)	BM (+)
Control	13.985±1.10 ^{d}	15.172±0.42 ^{d}	0.070±0.005 ^{c}	0.077±0.004 ^{c}
KOH (1/2)	22.487±0.72 ^{bc}	27.155±0.52 ^{ab}	0.096±0.001 ^{bc}	0.108±0.005 ^{ab}
KOH (F)	18.643±1.32 ^{cd}	29.518±2.69 ^{a}	0.068±0.006 ^{c}	0.119±0.005 ^{ab}
K2SiO3(1/2)	19.721±1.01 ^{cd}	28.102±2.30 ^{ab}	0.083±0.002 ^{bc}	0.121±0.010 ^{a}
K_2SiO_3 (F)	20.428±0.23 ^{cd}	25.198±0.52 ^{abc}	0.062±0.008 ^{c}	0.101±0.003 ^{abc}
SEm(±)	1.33		0.00001	
LSD(α=0.05)	3.93		0.017	
CV (%)	10.48		11.03	
F-Probability	*		*	
Grand Total	19.052	25.029	0.075	0.105

Overall, moderate doses of alkaline amendments combined with B. megaterium RK1 provided the best outcomes, likely by optimizing pH adjustment without overcorrecting, supplying essential base cations, and stimulating microbial-mediated nutrient cycling. These results highlight the importance of integrated chemical and biological management for restoring microbial function and soil fertility in acidic environments.

Conclusions

The combined application of alkaline amendments and Bacillus megaterium var. phosphaticum RK1 proved effective in improving key soil chemical and biological properties in acidic soil. pH correction through KOH and K_2SiO_3 reduced exchangeable acidity and enhanced phosphorus availability, particularly when paired with microbial inoculation. While short-term changes in organic matter were minimal, microbial biomass carbon and basal respiration increased significantly under integrated treatments, reflecting improved microbial activity and nutrient cycling. Moderate amendments often outperform full rates, suggesting that balanced inputs can optimize soil conditions without causing chemical imbalances. These results highlight the value of integrated biological and chemical management strategies for restoring fertility and productivity in phosphorus-limited acidic soils.

Acknowledgement

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The Productivity Potential of The Lands of Nehram Village in The Nakhchivan Autonomous Republic

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Abstract

This study investigates the complex interrelationship between soil characteristics, productivity issues, and solutions in the landscapes of Nehram village in the Nakhchivan Autonomous Republic (NAR). The aim of this research is to assess the physical and chemical properties of soil samples taken from these fields, with a focus on nutrients. By synthesizing these perspectives, the study enriches the understanding of the complex relationship between soil fertility class and productivity, while offering ideas for sustainable fruit growing. Soil samples were collected from the Nehram village area and analyzed according to various parameters: soil texture, pH, electrical conductivity, organic matter, and nutrient content. The process of sample collection and preparation preserved the integrity of the collected samples, providing a reliable basis for scientific analysis. The results reveal various soil characteristics, with a dominance of sandy and loamy textures. The deficiency of nutrients in the soil creates problems, highlighting the need for their correction. Most of the soils have inappropriate pH levels, indicating that interventions such as soil neutralization are necessary. Low organic matter and nutrient deficiencies suggest the need for targeted interventions. The study emphasizes the importance of adapted strategies in solving specific regional problems and provides valuable information for local practices and the broader global search for sustainable productivity. Aim of study is to investigate the physical and chemical soil properties in Nehram village (Nakhchivan, Azerbaijan) and assess their impact on soil fertility and fruit productivity, in order to propose sustainable soil management strategies.

Keywords: Sandy soil, humus, sustainable productivity, stone fruits

Introduction

Peach is the second most important stone fruit crop globally, both in terms of economic and nutritional value (Dana et al., 2021, 2008). Stone fruit plants are perennial, meaning they live and yield crops for many years once planted. The normal growth, development, longevity, and high-quality yield of these plants also depend on the characteristics of the soil. The condition of the plant's aerial system is largely dependent on the condition of its root system. If the plant is grown in soil that is not suitable for it, it fails to grow normally and eventually dies. The relationship of stone fruit plants with soil depends on the species, variety, and rootstock type. If the soil meets the plant's requirements, its root system extends deeply and outward, supplying the aerial part with nutrients and water. Under such conditions, the cultivated plant becomes long-lived and produces abundant and high-quality crops. However, when grown in soil types that are not conducive to growth, the root system of the plant cannot develop properly, and it cannot provide the aerial part with adequate nutrients and water. In such conditions, the plant produces low-quality and small yields, resulting

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in a short lifespan. To maintain peach productivity and quality, the application of fertilizers is generally necessary. However, excessive use of fertilizers has led to negative effects such as low fertilizer use efficiency and high nitrogen loss (Gao et al., 2012).

Material and Methods

Study Area

Soil samples were taken from the Nakhchivan AR Nehram village at the end of the cereal harvest, from depths of 0-30 cm and 30-60 cm. An orchard (apricot, peach, plum) is planned to be established in the area. After the harvest, soil samples were carefully collected, representing the entire area. The collected soil samples were thoroughly cleaned of stones and plant residues from the soil surface. The soil samples were then transported to the laboratory for analysis and processed under controlled laboratory conditions. To prevent changes in the chemical composition due to excessive heat or sunlight, the samples were initially air-dried in a cool, shaded environment. After drying, the remaining moisture was removed, and the soil samples were crushed. The soil samples were then sieved through a 2 mm sieve to achieve a consistent particle size for optimal analytical results. The prepared, homogeneous, and finely ground soil samples were considered ready for analytical purposes and used in subsequent research. The entire process of collecting and preparing the soil samples aimed to preserve the integrity of the collected samples and create a reliable basis for the scientific analysis of the soil properties of the designated area (Guliyev, 2014a,b).

Soil Analyses: pH, EC – Water extraction (Jones, 1930); P_2O_5 – Olsen; N – easy hydrolysis (Cornfield method); K_2O – Maslova method; Cation-anion composition in water – GOST 26423-85 / 26428-85; Ca and Mg ions – GOST 26487-85; Humus – Turin method; Sulfur – GOST 26490-85.

Climate. The Autonomous Republic has a sharply continental climate, and depending on the topographical features, the climate types vary. In the Araz river plain, a semi-desert and dry steppe climate is present with hot summers and cold winters. In the mountains, a dry and cool summer climate prevails, while at the high mountain sections of the Zangezur range (3800-3900 m), the mountain tundra climate type is formed. The number of sunshine hours is between 2600-2800 hours in the plains and 2000-2400 hours in the high mountains. Solar radiation is 140-160 kcal/cm^2, and the annual radiation balance fluctuates between 25.0-45.0 kcal/cm^2. Precipitation is unevenly distributed in the region. In the sloping plains along the Araz river and low mountain zones, precipitation is between 200-400 mm, while in the medium and high mountain zones, it reaches 600-800 mm.

Results and Discussions

One of the key indicators of soil is its ability to conduct water and air. Soils with sufficient water and air permeability are favorable for fruit plants. High soil density (bulk density) generally has a negative impact on plants. It has been determined that cherry and apricot cannot develop in soils with a bulk density of 1.5 g/cm^3. The analysis results revealed that the area consists of sandy and loamy soil types.

Table 1. Granulometric Analysis of Soil

Coordinates	Sand (1-0.05 mm)	Silt (0.05-0.002 mm)	Clay (<0.002 mm)	Soil Type
Ta-0021	85.54%	9.61%	3.85%	Sandy loam
Ta-0022	97.00%	2.00%	1.00%	Sandy
Ta-0023	96.22%	2.38%	1.4%	Sandy
Ta-0024	87.82%	11.11%	1.07%	Sandy loam
Ta-0025	93.22%	4.76%	2.02%	Sandy

The role of hydrogen ions concentration (pH) in the soil solution is significant in the life of fruit plants. As the analysis results show, the pH (H_2O) ranges between 8.01 and 8.52 (high), which will hinder the absorption of phosphorus and micronutrients. The electrical conductivity of the soil sample is high.

Fruit plants have low nutrient demand until they start bearing fruit. However, once they begin to fruit, their demand for nutrients increases. Different fruit plants absorb a certain amount of nutrients from the soil to produce each quintal of fruit. For example, in high-yield years, plum and peach plants absorb 34-85 kg of nitrogen, 10-20 kg of phosphorus, 44-82 kg of potassium, and 47-130 kg of calcium per hectare. According to the analysis results, the humus content in the Ta-0021 soil sample is very low. The nitrogen content in the soil samples is below the normal level. The phosphorus absorbed in the Ta-0021 sample is within the normal range, while the other samples show lower values (Alcordo et al., 1993). The potassium content in the soil samples is above the normal level.

Table 2. Nutrients content of soil.

Depth	pH	EC, mS/cm (1:1)	Organic matter, %	Available N, mg/kg	Available P_2O_5, mg /kg	Exchangeable K_2O, mg/kg
Ta-0021	8.01	1.36	2.08	91	24.00	975
Ta-0022	8.10	1.29	0.96	42	8.00	609
Ta-0023	8.52	0.49	0.83	42	9.60	532
Ta-0024	8.20	1.30	0.97	35	11.74	720
Ta-0025	8.49	0.81	0.75	28	8.90	594

According to their relationship with calcium, fruit and berry plants are divided into two major groups. Plants that require a high concentration of calcium (lime) in the soil are called calcephile plants. Stone fruit plants are included in this group. Chloride and saline soils negatively affect the growth and development of fruit plants. The presence of 0.5% sodium chloride in the soil has a lethal effect on plants. It should not exceed 0.005% in the soil. In conditions where the concentration of dissolved salts in water is 0.43%, fruit plants grow normally. However, in conditions where this concentration reaches 1.2%, the plant dies. In soils containing sodium, stone fruit plants grow normally. The salt tolerance of different fruit plants is not the same. While some fruit plants do not grow in saline soils, apricots, plums, and peaches grow normally. For plants to grow and develop properly, soils are required that retain water normally, create a balance between air and water regimes, and are fertile and structured. In Ta-0024, the Cl (chlorine) and in Ta-0021, 0024, 0025, the HCO3 (bicarbonate) ions exceed the toxicity threshold (Allison et al., 1954).

Table 3. Determination of Cation-Anion Composition of Soil in Water, mg-equiv/100 g of soil

Sample	HCO_3	Norm (max.)	Cl	Norm (max.)	Ca+Mg	Na	Norm (max.)	K	SO_4	Norm (max.)	Total salt content, %
Ta-0021	0.85	0.8	0.30	0.3	1.55	0.6	1	0.06	1.06	1.7	0.16
Ta-0022	0.65	0.8	0.25	0.3	1.50	1.0	1	0.10	1.70	1.7	0.19
Ta-0023	0.75	0.8	0.15	0.3	1.00	0.1	1	0.01	0.21	1.7	0.08
Ta-0024	0.95	0.8	0.40	0.3	1.50	0.2	1	0.02	0.37	1.7	0.13
Ta-0025	1.05	0.8	0.20	0.3	1.25	0.1	1	0.01	0.11	1.7	0.10

Based on the analysis results, the magnesium content in the soil samples is much higher than the normal range. In soil samples Ta-0022 to Ta-0025, the calcium content is medium, while in Ta-0021, it is high (Abrol et al., 1988).

Table 4. Determination of Available Ca, Mg Ions, and Sulfur (S)

Sample	Ca^{2+} (mg/kg)	Availability	Mg^{2+} (mg/kg)	Availability	S (mg/kg)	Availability
Ta-0021	3055.95	High	653.20	Very High	131.8	High
Ta-0022	2755.36	Medium	622.82	Very High	145.4	High
Ta-0023	2003.9	Medium	562.05	Very High	34.5	Low
Ta-0024	2605.07	Medium	531.67	Very High	91.4	Medium
Ta-0025	2454.78	Medium	546.86	Very High	45.2	Low

Conclusions

In conclusion, this study aims to comprehensively examine the physical and chemical properties of soil samples taken from agricultural lands in Nehrəm village, Nakhchivan AR, evaluate the nutrient content, soil characteristics, and potential limitations related to fruit production and plant nutrition. The results revealed various soil characteristics, including changes in pH levels, salinity, and nutrient content. High pH poses significant barriers for fruit orchards. Recommendations for corrective measures, including the application of acidifying materials and methods for restoring acidity and salinity, were discussed. Additionally, the study emphasized the importance of proper fertilization. It calls for tailored strategies to enhance local practices and contribute valuable insights for sustainable fruit production on a global scale. In summary, addressing identified soil issues and implementing appropriate corrective measures, along with precise fertilization strategies, will undoubtedly play a significant role in increasing the productivity of fruit orchards in Nakhchivan and, consequently, contribute to the global search for sustainable fruit farming.

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Determination of Changes in Microbial Respiration along Soil Profiles in Soils with Different Pedological Characterıstics

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Abstract

Soil biological functioning is closely linked to microbial metabolism and is strongly shaped by pedogenesis and depth-related gradients in soil properties. This study evaluated microbial respiration (MR) along soil profiles with contrasting pedological characteristics in the Kuşkonağı Basin (Havza District, Samsun Province, Türkiye) and examined its relationships with selected soil properties. Six soil profiles were excavated and sampled by genetic horizons, and soils were classified as Typic Haploxerept, Typic Calcixerept (two profiles), Lithic Xertorthent, Vertic Xerofluvent, and Chromic Haploxerept. Soil texture, pH, EC, $CaCO_3$, organic matter, total N, available P, exchangeable cations, and CEC were determined using standard methods, and MR was measured following Anderson (1982). Microbial respiration varied between 5.68 and 71.95 µg CO_2 g^{-1} 24 h^{-1} (dry soil basis) and generally decreased with increasing depth, indicating higher biological activity in surface and upper horizons. Correlation analysis showed significant positive relationships ($P < 0.01$) between MR and silt content ($r = 0.530$), pH ($r = 0.604$), EC ($r = 0.675$), $CaCO_3$ ($r = 0.693$), and exchangeable Ca ($r = 0.769$). The findings highlight that microbial respiration responds to integrated physicochemical controls along the profile and can serve as a practical indicator for assessing depth-dependent soil biological status across pedologically diverse soils.

Keywords: Microbial respiration; soil profile; pedogenesis; soil classification; depth gradient; physicochemical properties; Kuşkonağı Basin..

Introduction

Soil is a biologically active system in which microorganisms and their enzymes regulate the transformation of organic substrates and the cycling of nutrients. Enzymes produced by soil microorganisms catalyze key biochemical reactions—such as hydrolysis, oxidation–reduction, dehydrogenation, ammonification, and nitrification—thereby converting complex polymers (e.g., cellulose, lignin, proteins, phosphoesters, carbohydrates) into smaller molecules that can be assimilated by the biota (Haktanır, 1973; Babu et al., 2010). In this context, soil biological functioning cannot be adequately represented by microbial counts alone; rather, functional indices that integrate microbial metabolism are required (Lorenz and Kandeler, 2004; Antisari et al., 2010).

Soil microbial respiration (MR), commonly quantified as CO_2 evolution under controlled laboratory conditions, is widely used as an indicator of overall microbial metabolic activity and soil biological quality. MR reflects the decomposition of soil organic matter by microbial communities, and therefore responds rapidly to changes in substrate availability and edaphic controls. In many studies, MR is strongly linked with soil organic matter and nutrient availability—particularly nitrogen—underscoring its relevance for soil fertility

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assessment and management decisions (Weldmichael et al., 2020) (Jonasson et al., 1996; Kızılkaya et al., 2010).

A critical, yet sometimes underemphasized, dimension in interpreting soil biological indicators is soil depth. Soil properties and the microenvironment experienced by microorganisms shift markedly along the soil profile due to changes in organic matter inputs, aeration, moisture regime, mineralogy, and nutrient status. As a consequence, microbial biomass, enzymatic activities, and carbon mineralization commonly decline with depth, and microbial community structure can change substantially from surface to subsoil horizons (Xu et al., 2021) (Lorenz and Kandeler, 2004; Marinari and Vittori Antisari, 2010; Babu et al., 2010). Moreover, depth-wise variation in MR can be significant even across relatively shallow intervals (e.g., 0–10 vs. 10–25 cm), with MR often exhibiting strong positive associations with soil organic matter and available nitrogen pools (Weldmichael et al., 2020) (Jonasson et al., 1996).

In addition to depth, soil structure and texture regulate microbial habitat quality and substrate accessibility. Aggregate organization and associated organic carbon fractions can strongly influence respiration rates, and recent work has demonstrated that MR and organic carbon typically decrease with depth while being modulated by structural units such as aggregate fractions and, in some landscapes, altitude (Jozedaemi and Golchin, 2024). Furthermore, topographic variability can contribute to spatial differences in soil properties and biological activity, including enzyme-related indicators, within short distances (Dengiz et al., 2007). These insights collectively suggest that evaluating MR within a pedological framework—i.e., across horizons, profiles, and soil taxa—provides a more realistic understanding of biological functioning and its controlling factors.

Therefore, the objective of this study was to determine the variation of microbial respiration along soil profiles developed under different pedological characteristics in the Kuşkonağı Basin (Samsun, Türkiye), and to examine relationships between microbial respiration and selected physical and chemical soil properties across horizons. By preserving horizon-based sampling and a standardized MR measurement approach, this study aims to clarify how pedogenesis-linked variability and depth gradients shape microbial metabolic activity.

Material and Methods

Study area

The study was conducted in the Kuşkonağı Basin, located within Havza District, Samsun Province (Türkiye) (Figure 1). The basin extends between 4548–4544 (UTM-km northing) and 718–724 (UTM-km easting). The landscape is predominantly undulating, consisting of gently sloping ridge-top flats and valley-bottom positions, which generate marked variability in soil-forming conditions within short distances. Land use is dominated by arable cropping, and the major cultivated crops in the basin include wheat, sunflower, and maize. According to long-term climatic averages, the region has a mean annual air temperature of 14,2 °C and a mean annual precipitation of 680,0 mm.

Soil profile excavation, description, and sampling

Within the Kuşkonağı Basin, six soil profiles were excavated to represent the main physiographic positions and the spatial variability of soils across the basin. Each profile was opened to a depth sufficient to expose the diagnostic horizons, and soil horizons were identified in the field. Soil samples were collected horizon-by-horizon from each profile. Samples were placed in clean containers, transported to the laboratory, and prepared for subsequent analyses.

Laboratory analyses of soil physical and chemical properties

All laboratory determinations were conducted on prepared soil samples following standard procedures. Soil texture (sand, silt, and clay fractions) was determined using the hydrometer method. Soil pH and electrical conductivity (EC) were measured in a 1:2,5 (w/v) soil:water suspension using calibrated pH and EC meters. Carbonate content ($CaCO_3$) was determined by the Scheibler calcimeter method. Soil organic matter was measured by the Walkley–Black wet oxidation method, and total nitrogen (N) was determined using the Kjeldahl method. Available phosphorus (P) was extracted with 0,5 M $NaHCO_3$ and quantified accordingly.

Exchangeable base cations (Na, K, Ca, and Mg) were extracted using 1 N NH_4OAc, and cation exchange capacity (CEC) was determined using the Bower method. Soils were classified according to Soil Survey Staff (1999) based on field observations and laboratory results.

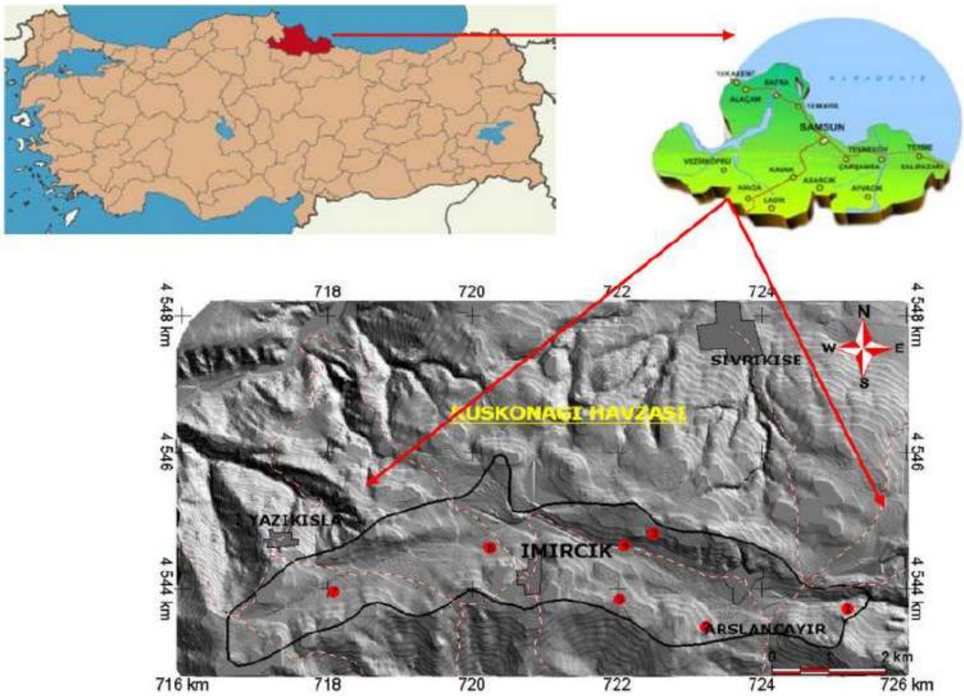

Figure 1. Study area map and the areal distribution of the points where soil profiles were opened.

Determination of microbial respiration

Soil microbial respiration was determined according to Anderson (1982) using an alkali (NaOH) CO_2-trapping approach. For each soil sample, 5 g of soil was weighed into incubation jars. A small tube containing 2,5 ml NaOH solution was placed inside each jar to absorb evolved CO_2. The jars were sealed and incubated for 10 days. After incubation, the NaOH solution was transferred to an Erlenmeyer flask, and 5 ml $BaCl_2$ solution was added to precipitate carbonate. A few drops of phenolphthalein indicator were added, and the residual alkali was titrated with 0,1 N HCl. Microbial respiration was expressed as CO_2 evolved per unit soil mass and time, consistent with the original method.

Statistical analysis

Relationships between microbial respiration and measured soil physical and chemical properties were evaluated using correlation analysis. Statistical significance was assessed at $P < 0{,}01$.

Results and Discussion

Soil classification and general physicochemical properties

Based on field morphological observations and laboratory data, the six soil profiles were classified as Typic Haploxerept (Profile 1), Typic Calcixerept (Profiles 2 and 5), Lithic Xertorthent (Profile 3), Vertic Xerofluvent (Profile 4), and Chromic Haploxerept (Profile 6). The horizon-wise physical and chemical properties are presented in Table 1 and Table 2.

Across all horizons, soils were generally slightly alkaline (pH 6,94–8,18) and non-saline to very slightly saline (EC 0,04–0,34 dS m^{-1}) (Table 1). Organic matter contents were generally low (0,24–3,48%) and showed clear stratification with depth, with higher values in surface horizons—most notably in the A1 horizon of Profile 6 (3,48%) and the Ap horizons of Profiles 1 and 5 (2,54% and 2,35%, respectively) (Table 1). Lime contents were variable (0,63–16,03%) and were particularly high in the calcic profiles (e.g., Profile 2 Bk horizon: 16,03%) (Table 1).

Total nitrogen followed a pattern similar to organic matter, with generally higher contents in surface horizons (e.g., Profile 6 A1: 0,25%; Profile 1 Ap and Profile 5 Ap: 0,19%) and lower values in deeper horizons (e.g., Profile 2 C1: 0,04%) (Table 2). Available P showed substantial variation among horizons and profiles, reaching higher values in some surface horizons (e.g., Profile 1 Ap: 29,19 mg kg^{-1}; Profile 6 A1: 28,52 mg kg^{-1}) while declining to very low levels in deeper horizons (e.g., 0,01 mg kg^{-1} in Profile 2 C1 and Profile 5 Ckss; Table 2). Exchangeable Ca and CEC also varied widely, reflecting differences in clay content, carbonate status, and pedogenic development (Table 2). Collectively, these results confirm that the basin includes soils with distinct pedological and geochemical characteristics, providing a suitable framework for evaluating microbial respiration responses across profiles.

Table 1. Selected physical and chemical properties of soil samples collected from the opened profiles

Profile / Soil Taxonomy	Horizon (Depth)	Sand, %	Silt, %	Clay, %	pH	EC (dS m^{-1})	O.M., %	Lime, %
Profile 1	Ap (0–19 cm)	34,54	21,66	43,80	7,06	0,10	2,54	1,03
(Typic Haploxerept)	Bw1 (19–50 cm)	37,02	18,77	44,21	7,01	0,08	0,24	0,99
	Bw2 (50–78 cm)	30,27	21,45	48,29	7,22	0,15	0,96	0,82
Profile 2	Ap (0–16 cm)	24,21	22,28	53,51	8,06	0,31	1,94	2,67
(Typic Calcixerept)	A2 (16–35 cm)	22,78	27,47	49,75	7,71	0,29	0,82	8,13
	Bw (35–60 cm)	23,97	34,94	41,08	7,80	0,25	0,48	13,20
	Bk (60–89 cm)	38,91	33,39	27,70	7,98	0,23	0,37	16,03
	C1 (89–110 cm)	74,47	14,97	10,56	8,18	0,14	0,32	6,13
Profile 3 (Lithic Xertorthent)	Ap (0–16 cm)	66,52	18,57	14,92	8,08	0,17	1,06	5,53
Profile 4	Ap (0–19 cm)	57,83	21,29	20,87	6,94	0,07	1,38	1,26
(Vertic Xerofluvent)	Bw (19–43 cm)	47,61	21,47	30,92	7,02	0,07	1,03	0,71
	C1 (43–98 cm)	45,28	19,64	35,08	7,23	0,09	0,99	1,38
	C2 (98+ cm)	70,67	10,02	19,31	7,14	0,04	1,30	1,28
Profile 5	Ap (0–18 cm)	22,93	24,65	52,42	7,16	0,16	2,35	1,39
(Typic Calcixerept)	Bss1 (18–56 cm)	21,43	22,46	56,10	7,55	0,19	1,03	0,95
	Bss2 (56–125 cm)	21,74	20,42	57,84	7,75	0,34	0,98	0,63
	Ckss (125+ cm)	22,05	23,40	54,55	8,11	0,34	0,39	10,66
Profile 6	A1 (0–15 cm)	26,97	24,33	48,69	7,03	0,31	3,48	1,47
(Chromic Haploxerept)	A2 (15–39 cm)	26,41	22,35	51,23	7,27	0,11	1,51	0,67
	Bss1 (39–70 cm)	25,44	23,27	51,29	7,45	0,15	1,32	0,88
	Bss2 (70–120 cm)	25,13	22,38	52,48	7,82	0,16	1,01	0,88
	Css (120+ cm)	25,27	21,26	53,46	8,02	0,32	0,58	1,47

Table 2. Selected chemical properties of soil samples collected from the opened profiles

Profile / Soil Taxonomy	Horizon (Depth)	Total	Av. P			(cmol kg^{-1})		
		N, %	(mg kg^{-1})	Na	K	Ca	Mg	CEC
Profile 1	Ap (0–19 cm)	0,19	29,19	0,13	0,78	20,95	6,59	43,74
(Typic Haploxerept)	Bt1 (19–50 cm)	0,14	6,62	0,19	0,33	23,68	8,00	56,05
	Bt2 (50–78 cm)	0,11	1,60	0,20	0,38	29,83	9,91	55,58
Profile 2	Ap (0–16 cm)	0,18	6,13	0,08	0,73	48,84	5,48	58,06
(Typic Calcixerept)	A2 (16–35 cm)	0,12	0,38	0,16	0,38	56,58	6,24	69,90
	Bw (35–60 cm)	0,09	3,31	0,14	0,28	57,84	6,43	53,27
	Bk (60–89 cm)	0,07	2,81	0,12	0,19	52,49	5,38	32,91
	C1 (89–110)	0,04	0,01	0,10	0,13	38,48	4,80	19,29
Profile 3 (Lithic Xertorthent)	Ap (0–16 cm)	0,07	6,96	0,06	0,38	44,29	3,46	26,81
Profile 4	Ap (0–19 cm)	0,10	13,76	0,03	0,53	10,25	2,47	15,33
(Vertic Xerofluvent)	Bw (19–43 cm)	0,12	4,60	0,07	0,66	16,85	3,75	30,66
	C1 (43–98 cm)	0,13	19,40	0,13	0,86	20,72	5,22	43,80
	C2 (98+ cm)	0,05	10,74	0,08	0,75	16,39	4,82	27,46
Profile 5	Ap (0–18 cm)	0,19	22,05	0,11	1,20	35,29	10,59	47,47
(Typic Calcixerept)	Bss1 (18–56 cm)	0,12	0,38	0,18	0,42	37,23	11,78	64,81
	Bss2 (56–125cm)	0,10	0,38	0,21	0,37	37,91	12,60	60,19
	Ckss (125+ cm)	0,06	0,01	0,22	0,30	54,65	14,48	57,65
Profile 6	A1 (0–15 cm)	0,25	28,52	0,12	1,08	29,37	9,47	42,38
(Chromic Haploxerept)	A2 (15–39 cm)	0,16	17,82	0,18	0,47	30,97	9,23	51,08
	Bss1 (39–70 cm)	0,15	5,68	0,15	0,34	31,88	9,43	59,42
	Bss2 (70–120cm)	0,10	2,01	0,14	0,30	32,56	9,33	62,32
	Css (120+ cm)	0,07	0,01	0,14	0,30	40,53	10,93	40,48

Microbial respiration along soil profiles

Microbial respiration (MR) showed a pronounced depth-related pattern, with higher activity in surface/upper horizons and decreasing activity with depth, consistent with the vertical decline in organic matter and total nitrogen (Tables 1–2). This behavior is mechanistically expected because microbial metabolism is primarily governed by the availability of labile organic substrates and nutrients, which are typically concentrated near the surface due to plant residue inputs and root activity.

In the original study, microbial respiration values were reported to range from 5,68 to 71,95 µg CO_2 g^{-1} 24 h^{-1} (dry soil basis), indicating substantial variability across horizons and pedological units. This range is summarized in Table 3 and illustrated in Figure 2. Similar depth-dependent reductions in soil respiration have been widely documented, where declines in substrate supply and shifts in microbial community functioning occur with increasing depth (Weldmichael et al., 2020; Xu et al., 2021). In addition, recent evidence emphasizes that respiration patterns can also be modulated by structural organization and aggregate-associated carbon pools, which vary with soil formation and depth (Jozedaemi and Golchin, 2024).

Microbial respiration (MR) showed a pronounced depth-related pattern, with higher activity in surface/upper horizons and decreasing activity with depth, consistent with the vertical decline in organic matter and total nitrogen (Tables 1–2). This behavior is mechanistically expected because microbial metabolism is primarily governed by the availability of labile organic substrates and nutrients, which are typically concentrated near the surface due to plant residue inputs and root activity. Similar depth-related declines in biological indicators and respiration have been reported across diverse soil profiles and land-use settings (Lorenz and Kandeler, 2004; Antisari et al., 2010; Marinari and Vittori Antisari, 2010; Kızılkaya et al., 2010).

Relationships between microbial respiration and soil properties

Correlation analysis revealed significant positive relationships ($P < 0,01$) between microbial respiration and silt content ($r = 0,530$), pH ($r = 0,604$), EC ($r = 0,675$), lime/$CaCO_3$ ($r = 0,693$), and exchangeable Ca ($r = 0,769$). These associations reflect the integrated controls of soil texture and geochemical environment on microbial metabolic activity.

The positive relationship with silt content may indicate improved water retention and more favorable microhabitats for microbial activity in siltier horizons, while also reflecting changes in organo-mineral interactions that influence substrate accessibility. The association with pH is consistent with the well-established sensitivity of microbial processes to soil reaction, where near-neutral to slightly alkaline conditions may sustain higher metabolic activity depending on substrate supply. In this dataset, the soils were predominantly slightly alkaline (Table 1), which can support active decomposition in surface horizons where organic substrates are more abundant.

Although EC values were low overall (Table 1), the positive MR–EC relationship likely reflects co-variation with other soil chemical features (e.g., base status and carbonate-related ionic composition) rather than salinity stress. The strongest association was observed with exchangeable Ca ($r = 0,769$) and $CaCO_3$ ($r = 0,693$). Calcium and carbonate status can influence aggregation, pore architecture, and organo-mineral stabilization, which together shape oxygen diffusion and substrate protection/accessibility. This pedological context is important because respiration is not driven by chemistry alone but also by the physical habitat in which microbial communities operate (Jozedaemi and Golchin, 2024). The strongest association was observed with exchangeable Ca ($r = 0,769$) and $CaCO_3$ ($r = 0,693$). Calcium and carbonate status can influence aggregation, pore architecture, and organo-mineral stabilization, which together shape oxygen diffusion and substrate protection/accessibility. In soils, enzyme activities and respiration-related indicators have repeatedly been shown to co-vary with physicochemical properties, supporting the interpretation that these correlations reflect integrated habitat and substrate controls (Kızılkaya et al., 2007; Dengiz et al., 2007).

Overall, these results support the interpretation that microbial respiration in the Kuşkonağı Basin soils is governed by a coupled set of textural and chemical factors along the profile. Nevertheless, correlations should be interpreted as indicators of co-occurring controls rather than direct causality, and future work including horizon-level MR measurements would allow stronger inference on mechanistic drivers.

Implications for soil quality assessment and management

The consistent decline of MR with depth demonstrates the importance of profile-based biological assessment rather than relying solely on surface sampling. This is aligned with depth-explicit soil biology literature showing that biological functioning decreases with depth and that surface measurements can overestimate the biological status of deeper horizons (Weldmichael et al., 2020; Xu et al., 2021). From a management perspective, practices that maintain or enhance surface organic inputs (e.g., residue retention, organic amendments, erosion control) are expected to sustain higher microbial activity in biologically active horizons, thereby supporting nutrient cycling and soil functional quality. From a management perspective, practices that maintain or enhance surface organic inputs (e.g., residue retention, organic amendments, erosion control) are expected to sustain higher microbial activity in biologically active horizons, thereby supporting nutrient cycling and soil functional quality. Evidence from organic-input studies also indicates that microbial properties respond sensitively to changes in organic substrate supply and soil environment (Kızılkaya and Hepşen, 2007).

Conclusion

This study demonstrated that soils in the Kuşkonağı Basin exhibit clear pedological and horizon-level variability, and that microbial respiration reflects these differences in a depth-explicit manner. Across six profiles representing Typic Haploxerept, Typic Calcixerept, Lithic Xertorthent, Vertic Xerofluvent, and Chromic Haploxerept soils, microbial respiration ranged from 5.68 to 71.95 µg CO_2 g^{-1} 24 h^{-1} (dry soil basis) and generally declined with increasing depth, supporting the presence of greater biological activity in surface and upper horizons where organic inputs and nutrient availability are typically higher.

Significant positive correlations ($P < 0.01$) between microbial respiration and silt content, pH, EC, $CaCO_3$, and exchangeable Ca indicate that microbial metabolic activity in these soils is governed by a coupled set of physical (textural/microhabitat) and chemical (soil reaction and base/carbonate status) controls rather than a single dominant factor. Collectively, the results emphasize the value of horizon-based sampling and pedological context when interpreting soil biological indicators. Microbial respiration, as applied here, provides a practical and sensitive metric for comparing biological status across soil profiles and for supporting soil quality assessment and management decisions that explicitly consider vertical (depth) variability.

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Organization of Effective Soil Management in the Gusar-Gonagkend Cadastral District of Azerbaijan

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Abstract

The study of the soils in the Gusar-Gonagkend cadastral district, which are intensively used in the agricultural sector of the Republic of Azerbaijan, revealed significant problems related to the improper and inefficient use of land resources. The research examined various anthropogenic impacts that significantly affect the environmental situation during land use in the cadastral region. Field and soil surveys of the cadastral district were conducted, and selected samples were analyzed using generally accepted methods, providing qualitative and environmental assessments. It was established that within the cadastral district, non-eroded areas make up 43.9%, while eroded areas account for 56.1%. Of these, severely eroded areas comprise 40.1% (33,029 ha), slightly eroded – 26.8% (22,075 ha), and moderately eroded – 33.1% (27,264 ha). Unsustainable logging in many sections of forested areas within the cadastral district, combined with the lack of reforestation efforts, has led to a reduction in forest-covered areas; forests occupied only a small portion—49,111 ha, which is merely 10.81% of the total area. It was found that soil fertility in the study area has declined due to intensive agricultural use: 16.92% of soils belong to the first quality group, 51.88% to the second group, 27.69% to medium-quality soil, and 3.51% to low-quality soil. Solonetzification was noted only in mountain-gray-brown soils—24.6%. To ensure environmental safety and ecosystem sustainability in the Gusar-Gonagkend cadastral district, key directions for sustainable land resource management have been identified. A conceptual framework has been developed to ensure the efficient use and protection of soils based on defining proper and effective land-use ratios for areas involved in intensive economic activities, along with an appropriate system of agrotechnical regulations. These include erosion control measures, forest protection and expansion, improvement of agricultural land use, creation of protective forest belts, prevention of soil alkalinity, expansion of perennial plantations, and others.

Keywords: agrotechnical measures deforestation, soil erosion, solonetzification, soil management

Introduction

Issues of efficient use of soil resources and land protection are among the important state issues and are considered one of the main strategic directions of public administration. In the modern era, in the conditions of high development of science and technology, along with fundamental scientific research aimed at studying the degradation processes occurring in soils, natural conditions of specific regions and the development of new scientific, methodological, legal and organizational approaches aimed at standardizing and assessing the ecological state of the natural environment and soils, taking into account their economic significance, has

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begun to acquire great significance. In this regard, attentions is drawn to their novelty and the effectiveness of various methods used by scientists from different countries of the world in relation to the assessment and protection of soil fertility (Mammadov and Yusifova, 2013; Hounkpatin et al. 2022; Chen et al. 2022; Kibret et al. 2023; Abdu et al. 2023; Hammad et al. 2024; Regasa et al. 2024; Daniel et al. 2024; Fatimazahra et al. 2025). In connection with this, the main goal of our research works is the development of measures for agroecological assessment, protection and effective soil fertility management of Gusar-Gonagkend cadastral district, located on the north-eastern slope of the Greater Caucasus.

Material and Methods

Study Area

The object of our research are the soils of the Gusar-Gonagkend cadastral district, the total area of which is 453932 ha. In the course of the research, we used materials on the soil cover of the Gusar-Gonagkend cadastral district, fund and literature materials of the Institute of Soil Science and Agrochemistry of the Ministry of Science and Education of Azerbaijan, a soil map of the northeastern slope of the Greater Caucasus on a scale of 1:100000, the results of laboratory studies, as well as the results of our studies (Babayev et.al. 2017).

When compiling the soil quality assessment scale for the Gusar-Gonagkend cadastral district, methodological recommendations by Karmanov (1975) and Mammadov (1997) were used.

To achieve the set objectives, soil field studies were conducted, 38 soil samples were taken, and laboratory analysis of the collected soil samples was carried out using generally accepted methods. Additionally, fund materials on soil fertility indicators were gathered.

Results and Discussions

The Gusar-Gonagkend cadastral district is located on the northeastern slope of the Greater Caucasus and covers an area of 5.24% of the total territory of the republic. The Gusar-Gonagkend cadastral district includes low-mountain and mid-mountain areas, as well as partially high-mountainous regions of the Gusar, Guba, Shabran, Siyazan, and Khizi districts. The elevation of the territory ranges from 115–250 meters in the north to 950–1500 meters in the south (Babayev et.al. 2017). In the high-mountain zone of the district, mountain-meadow soils are prevalent; in the mid-mountain zone, mountain-forest brown soils dominate; while in the low-mountain zone, mountain-cinnamon and mountain-gray-brown soils are widespread (Isayeva, 2018).

Protection and Effective Management of Land Fertility in the Gusar-Gonagkend Cadastral District

During the land survey of the Gusar-Gonagkend cadastral district, important problems related to the targeted and irrational use of land resources were revealed, which made it necessary to improve the system of effective use of intensive land use in agriculture. According to our studies, each soil-climatic zone underwent changes to one degree or another. Below is a brief description of the main problems that arise during land use in the studied area.

Soil erosion

Based on archive and cartographic materials, it was established that 32.8% of mountain meadow soils located in the high-altitude zone of the Gusar-Gonagkend cadastral district are not subject to erosion, and 67.2% (115,565 hectares) are subject to erosion of varying degrees (Table 1).

Since primitive and soddy-peaty subtypes of mountain meadow soils are more susceptible to erosion, these lands are subject to severe erosion (45.3%, 52,351 hectares), and 31% of the area (35,825 hectares) are subject to erosion. It was established that 27,389 hectares of mountain meadow soils are subject to moderate erosion. Due to non-compliance with grazing regulations, as well as unregulated and excessive livestock grazing on summer pastures in the study area, the condition of pastures and hayfields has significantly deteriorated, leading to widespread pasture erosion (Isayeva, 2024). Deforestation in the forested zone of the Gusar-Gonagkend cadastral district has intensified surface erosion, significantly degrading forest plantations and weakening natural regeneration. Due to non-compliance with grazing regulations, as well as unregulated and excessive livestock grazing on summer pastures in the study area, the condition of pastures and hayfields has significantly deteriorated, leading to widespread pasture erosion.

Deforestation in the forest zone of the Gusar-Gonagkend cadastral district has increased surface erosion, significantly degrading forest stands and weakening natural regeneration. The relief in areas where mountain-forest brown soils are distributed is represented by highly dissected mid-mountain areas and mountain-valley depressions, densely cut by mountain rivers, which makes it extremely susceptible to severe erosion (Tagiyev, 2013). Analyzing the degree of erosion of the mountain-forest zone of the Gusar-Gonagkend cadastral region, we note that erosion covers almost half of the area (48.9%). Weak erosion (53.2%, 10,502 ha) is more common here than medium (24%) and strong (22.8%) (Table 1).

Table 1. Degree of soil erosion in the Gusar-Gonagkend cadastral district

Soils	Total area, ha	Degree of erosion				
		Non-eroded area	Eroded area	including		
				week	moderate	severe
Mountain-meadow	171973 / 37,89	56408 / 32,8	115565 / 67,2	35825 / 31,0	27389 / 23,7	52351 / 45,3
Mountain-forest	40370 / 8,89	20629 / 51,1	19741 / 48,9	10502 / 53,2	4738 / 24,0	4501 / 22,8
Mountain-cinnamon steppe	146824 / 32,34	64456 / 43,9	82368 / 56,1	22075 / 26,8	27264 / 33,1	33029 / 40,1
Mountain gray-brown	58486 / 12,88	35576 / 60,8	22910 / 39,2	8797 / 38,4	8133 / 35,5	5980 / 26,1
Total	453932 / 100	212440 / 46,8	241492 / 53,2	100702 / 41,7	74380 / 30,8	66410 / 27,5

Reduction of Forest Resources

At the beginning of the 19th century, forests covered 30% of the territory of Azerbaijan. Currently, the total area of the forest fund of Azerbaijan is 1,213,700 ha, of which 1,040,300 ha (11.8%) are forest massifs, which is about 0.12 ha of green plantations per capita.

In the Gusar-Gonagkend cadastral district, the forest cover is mainly concentrated in mid-mountain and low-mountain areas at an altitude of 600-1500 meters above sea level. In these forests, oak, hornbeam and beech prevail, and steppe birch, alder, elm and eastern apple are the subdominants.

The study revealed that the following degradation processes are occurring in the forests of the Gusar-Gonagkend cadastral district as a result of anthropogenic impact: reduction of forested areas, degradation of tree species, reduction in productivity, replacement of forest soils with steppe soils, loss of valuable plant species, deterioration of the sanitary condition of forests, and depletion of wood resources.

Decline in Soil Fertility

According to the research of Aliyev (1990), in the eroded types of steppe mountain cinnamon soils in the Gusar and Guba districts, the amount of humus and absorbed bases decreases. In the upper layer of moderately eroded soils, the humus content has decreased by 1.75–1.79%, while in severely eroded soils, it has decreased by 0.98–1.1%.

According to the research of Babayev et al. (2017), the humus content in mountain gray-cinnamon soils cultivated under monoculture (1.4–2.0%) has significantly decreased compared to virgin soils under shrubs and steppe vegetation (2.0–4.5%). The author attributes the decline in humus, total nitrogen, and absorbed nutrients in cultivated mountain gray-brown soils to prolonged monoculture grain farming, insufficient application of organic and mineral fertilizers, and failure to follow proper agronomic practices in crop rotation.

According to the research of Abdullayev (2014), 269 hectares of cultivated land in the study area have become completely unsuitable for agriculture, 393 hectares have undergone severe degradation, 7,791 hectares have suffered moderate degradation, and 5,762 hectares have experienced week degradation.

Based on the analysis of our own research and archive materials, we have classified the soils of the Gusar-Gonagkend cadastral district by quality groups (Table 2). According to the table, 44.58% (65,458 ha) of the lands used for perennial plantings are classified as high quality, 34.82% as good, and 20.60% as medium in quality.

Table 2. Distribution of arable lands and soils under perennial plantings of the Gusar-Gonagkend cadastral district by quality groups

Soil Quality Groups	For perennial crops		For arable land	
	Ha	%	Ha	%
I – High quality soils	65458	44.58	11562	16.92
II – Good quality soils	51120	34.82	35460	51.88
III – Medium quality soils	30246	20.60	18924	27.69
IV – Low quality soils	-	-	2400	3.51
Total	146 824	100,0	68346	100,0

It was established that in the low-mountain zone, 16.92% of the soils of the highest quality group and 51.88% (35,460 ha) of the second quality group are used for arable land (Fig. 1).

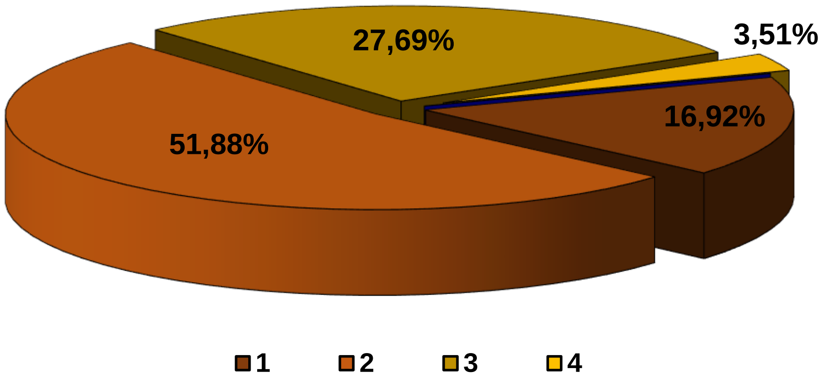

Figure 1. Distribution of arable lands of the Gusar-Gonagkend cadastral district by quality groups: 1 – high quality soils; 2 - good quality soils; 3 - mediumquality soils; 4 – low quality soils

Additionally, 27.69% of arable lands are classified as medium, and 2.4 thousand hectares (3.51%) are classified as low. All of the above once again confirms the decline in the fertility of the soils of the Gusar-Gonagkend cadastral district due to irrational farming.

Soil Alkalinity

Alkalinity is one of the factors contributing to the decline in the productivity of crops grown on irrigated lands in our republic. According to research by Mammadov (2007), 11.2% (508,270 ha) of Azerbaijan's agricultural lands are alkaline, of which 75.5% are weakly alkaline, 20.1% moderately alkaline, and 4.2% strongly alkaline. Among them, 2.8% of arable land, 10.3% of land under perennial plantations, and 17.1% of pastures and grazing lands have undergone alkalinity.

According to the soil map of the Gusar-Gonagkand cadastral district, 2.2% (10,000 ha) of the total area of the studied territory is subject to alkalinity, observed only in mountain gray-brown soils—24.6%, of which 23.4% (5,800 ha) are ordinary and 43% (4,200 ha) are light mountain gray-brown soils affected by weak alkalinity (Fig. 2).

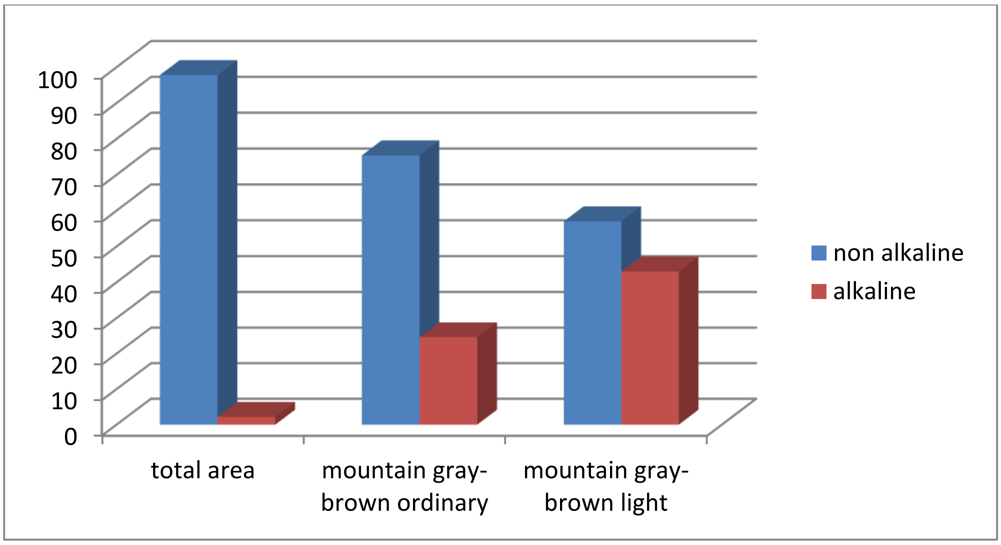

Figure 2. Soil alkalinity level in Gusar-Gonagkend cadastral district

Taking all the above into account, we have developed a conceptual framework to ensure the the effective management and protection of land resources based on the proper and effective spatial distribution and a system of corresponding agrotechnical regulations for the soils of the Gusar-Gonagkend cadastral district.

The main components of this framework include the implementation of anti-erosion measures, the protection and expansion of forested areas, the improvement of agricultural land use, the establishment of protective forest belts, the proper delineation of boundaries for farm enterprises, the expansion of perennial plantations, the prevention of soil alkalinity, and other related actions.

Ways to organize increasing fertility, effective use and protection of lands

Anti-erosion measures: Reduce livestock numbers and grazing duration on pasture areas that are slightly affected by erosion, and implement a rotational grazing system, in moderately eroded areas: reduce the number of large and small livestock by at least 25%, apply rotational grazing, introduce haymaking, and implement a sowing system. In severely eroded areas, it is advisable to halt livestock grazing for at least 2–3 years, apply a mowing system, implement lateral slope mitigation, eradicate poisonous and harmful plant species, apply mineral and organic fertilizers, and establish protective forest belts.

To restore the fertility of eroded lands in cultivated areas, the following measures are recommended: sowing row crops and cereals on areas with slight erosion, performing cultivation work across the slope during plowing and vegetation periods, and applying the necessary amounts of mineral and organic fertilizers.

On moderately and severely eroded arable lands, it is advisable to replace spring crops with autumn crops, sow seeds of perennial leguminous and cereal grasses, conduct transverse cultivation across slopes, create water-collecting furrows during plowing, maintain grass strips 3–5 meters wide every 15–29 meters, implement contour plowing on steep slopes, and apply organic and mineral fertilizers (Mammadov et al. 2011).

Forest Restoration and Expansion: The total forest area in the Gusar-Gonakgand cadastral district is 49,111 hectares (10.81% of the total area), which is the main reason for the mass deforestation in the district for agricultural purposes. In order to reduce the anthropogenic impact on the territory of the Gusar-Gonagkend cadastral district and create conditions for the self-restoration of natural ecosystems, it is necessary to increase the forest area in this territory to at least 30% of the total area, which implies an increase in the forest area from 49 thousand hectares to 136 thousand hectares.

According to the research of many scientists, in order to restore the forest cover of the territory, it is advisable to plant such tree species as rowan, almond, pistachio, Eldar pine, pear, and eucalyptus in the low-mountain zone on rocky slopes at an altitude of 500-600 m; in the lower forest zone on eroded rocky slopes – sedge pine, Crimean pine, and Scots pine; in the upper forest zone – Scots pine, pear, and birch (Dolkhanov et al. 2012).

Expansion of Perennial Plantations: Utilizing eroded slopes in the studied area for perennial plantations is a highly relevant issue. However, these lands must meet soil and ecological criteria to be suitable for orchards and vineyards.

When planting perennial crops on mountain slopes, it is recommended to arrange plantings in an inclined pattern, and under highly complex terrain conditions, in a contour pattern along the horizontal lines. The recommended plot size is up to 15 ha. Terracing is carried out on slopes with an inclination of 8–20°. On areas with slopes of 6–15°, the recommended plot dimensions are 250–400 m in length and 80–250 m in width (Mammadov et al. 2011).

Establishment of Protective Forest Strips: It is recommended to create forest strips in areas affected by erosion and unsuitable for use as pastures, grazing lands, or agricultural fields. The economic and reclamation efficiency of forests planted with oak is higher. In hilly areas prone to water erosion, forest strips should be established across the slope.

On slopes with an inclination of more than 20°, used for arable land, forest strips can be expanded up to 21 meters to reduce surface runoff. The recommended widths for forest strips are: 15 m on slightly eroded soils, 20–25 m on moderately eroded soils, 30 m on severely eroded soils.

For longitudinal placement of forest strips, the recommended distances are 600 m for mountain chernozems and mountain cinnamon soils, and 500 m for mountain gray-brown soils.

Prevention of Soil Alkalinity: According to research by various scientists, the agrobiological method is effective for improving the fertility of alkaline soils in the region. This method includes a combination of biological and agrotechnical measures: planting and deep plowing are carried out in layers containing $CaCO_3$ and gypsum to dissolve these compounds.

During this process, the application of mineral and organic fertilizers, as well as grass seeding with irrigation, is effective. Organic fertilizers improve the water-physical properties of alkaline soils, enrich them with mineral elements, and enhance microbiological activity. Additionally, since alkaline soils have a high demand for nitrogen and phosphorus, the use of nitrogen and phosphorus fertilizers is recommended (Mammadov et al. 2011). In areas with small and medium alkaline patches, it is advisable to apply a 2–3 cm layer of fertile soil to cover the affected spots.

Proper Allocation of Farm Boundaries: According to scientific research, farm boundaries should be arranged in a way that ensures favorable conditions for the internal organization of the land and its efficient and proper use. It is essential to avoid issues such as fragmentation of planting areas and the creation of irregularly shaped or inconveniently located plots.

Crop rotation is recommended for agricultural fields within farms. Since these farms are generally small, crop rotation may limit the variety of cultivated plants. However, experts emphasize its importance for soil conservation and erosion prevention (Mammadov et al. 2011).

As rainfed farming is practiced in the Gusar-Gonagkand cadastral district, it is effective to allocate land within the crop rotation system for fallow cycles (winter wheat, barley, alfalfa). Additionally, since livestock farming is also well developed in this area, it is beneficial to designate lands for alfalfa, sorghum, and maize within the crop rotation system.

As rainfed farming is practiced in the Gusar-Gonagkand cadastral district, it is effective to allocate land within the crop rotation system for fallow cycles (winter wheat, barley, alfalfa). Additionally, since livestock farming is also well developed in this area, it is beneficial to designate lands for alfalfa, sorghum, and maize within the crop rotation system.

Based on the "Strategic Roadmap for Agricultural Production and Processing in the Republic of Azerbaijan", measures aimed at enhancing market access for small farms in the Gusar-Gonagkend cadastral district include consolidation initiatives, restructuring family farms, and transitioning to a cooperative and contract farming system (https://static.president.az/pdf/38542.pdf). These steps will enable the implementation of advanced agrotechnical practices, ultimately leading to an increase in farm incomes.

Taking all the above into account, we have developed a conceptual framework to ensure the efficient use and protection of land resources based on the proper and effective spatial distribution and a system of corresponding agrotechnical regulations for the intensively managed soils of the Gusar-Gonagkend cadastral district. The main components of this framework include the implementation of anti-erosion measures, the protection and expansion of forested areas, the improvement of agricultural land use, the establishment of protective forest belts, the proper delineation of boundaries for farm enterprises, the expansion of perennial plantations, the prevention of soil salinization, and other related actions.

Conclusions

The types of anthropogenic impact that have a significant impact on the environmental conditions of land use in the Gusar-Gonagkend cadastral district (development of erosion processes, reduction of forest resources, decreasing of soil fertility, solonetzification, etc.) have been identified. It has been established that 56.1% of the land in the cadastral district is eroded to varying degrees, and 24.6% of mountain gray-brown soils are subject to solonetzification.

In order to ensure environmental safety and sustainability of the ecosystem in the Gusar-Gonagkend cadastral district, the main areas of effective use and protection of land resources have been identified and a system of relevant measures has been developed (implementation of anti-erosion measures, protection and expansion of forests, improvement of the use of agricultural lands, creation of forest shelterbelts, etc.).

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Identifying limitations and enhancement pathways for the WEPP model in simulating rill erosion: A focus on parameter uncertainty and hydraulic drivers

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Abstract

Background The Water Erosion Prediction Project (WEPP) model, developed and refined over the past four decades, is a cornerstone physically based tool for simulating soil erosion at hillslope and watershed scales. The model's development has been strongly informed by pioneering research in soil erosion processes and hydraulics. Despite its extensive use, limitations in parameter estimation and hydraulic representation still affect accuracy and applicability, especially in complex terrains and heterogeneous soils without site-specific calibration. Objectives This study aims to evaluate key limitations of the WEPP model in rill erosion simulation, emphasizing that these assessments are grounded in decades of foundational research. It also proposes potential enhancements to improve parameterization and hydraulic modeling. Methods The conceptual analysis focuses on WEPP's empirical estimation of hydraulic parameters such as rill erodibility and critical shear stress, which rely on intrinsic soil properties including clay content, organic matter, bulk density, and permeability. The model's dependence on shear stress as the primary soil detachment driver is examined in light of extensive experimental validation and historical developments in erosion modeling. Results Parameter estimation methods derived from intrinsic soil properties introduce notable uncertainty, especially in steep or structured soils. Refinements incorporating additional soil fractions and slope effects have improved accuracy but are still limited in scope. Empirical evidence consistently supports shear stress as the dominant hydraulic driver, aligning with WEPP's foundational assumptions. Operational challenges remain, including limited regional calibration data, lack of flexibility for diverse soils, and usability constraints. Conclusions Enhancing WEPP's predictive reliability requires further development of flexible, regionally adapted parameter estimation methods, improved calibration workflows, and more user-friendly interfaces. Maintaining emphasis on shear stress as the key hydraulic driver, supported by decades of experimental and theoretical research, will strengthen the model's applicability across diverse landscapes..

Keywords: WEPP model, rill erosion, shear stress, parameter uncertainty, hydraulic modeling, soil erosion simulation, model enhancement

Introduction

Over the past three decades, soil erosion research has undergone a fundamental shift from empirical prediction toward process-based simulation models (Nearing et al. 1990). Among these, the USDA Water Erosion Prediction Project (WEPP) is one of the most widely applied and well-documented models (Flanagan

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and Nearing, 1995; Flanagan et al. 2007). Designed as a physically based tool, WEPP represents a new generation of erosion prediction technology, integrating hydrological processes, soil–plant interactions, and erosion mechanics (Foster and Lane, 1987; Lane and Nearing, 1989). Its broad applicability extends to croplands, forestlands, and rangelands, supporting soil conservation planning, watershed management, and evaluation of alternative land use strategies.

Unlike the Universal Soil Loss Equation (USLE) and its revised version (RUSLE), which rely on empirical factors, WEPP simulates erosion processes on the basis of storm event runoff rates and a steady-state sediment continuity equation (Nearing et al. 1989). The model's modular structure incorporates multiple components, including climate generation, surface and subsurface hydrology, plant growth and residue decomposition, soil tillage effects, overland flow hydraulics, and erosion processes on hillslopes and channels. By linking these modules, WEPP is capable of predicting sheet and rill erosion, ephemeral gully development, channel erosion, sediment transport, and delivery to downstream water bodies under diverse environmental and management conditions.

The fundamental advantage of WEPP lies in its explicit representation of soil erodibility through physically based parameters, including interrill erodibility (Ki), rill erodibility (Kr), and critical shear stress (τcr) (Laflen et al. 1991; Flanagan et al. 2001; Nearing et al. 1997). These parameters enable a more precise distinction between hydraulic forces driving erosion and the intrinsic resistance of soils, thereby overcoming several limitations of USLE/RUSLE. Nevertheless, their estimation remains challenging, especially under varying soil textures, structural conditions, and moisture regimes. Experimental studies investigating the interactions among runoff hydraulics, rill detachment, sediment transport, and soil cohesion are still relatively scarce (Bryan, 2000; Elliot and Flanagan, 2023). This lack of robust parameterization often limits model accuracy in predicting rill and channel erosion, particularly for complex landscapes and heterogeneous soils where site-specific calibration is not available.

Since process-based models such as WEPP are expected to play a central role in future erosion prediction and soil conservation planning (Flanagan et al. 2007; Wu et al. 2017), improving parameter estimation and hydraulic representation is critical. Building on decades of foundational research in erosion science and hydraulics, this study focuses on evaluating key limitations of the WEPP model in simulating rill erosion. In particular, it highlights the challenges of parameter estimation and the need for refined process descriptions, while also proposing potential improvements that could enhance the reliability and applicability of the model across diverse soil and landscape conditions.

Material and Methods

The WEPP model is physically based on hydrologic and erosion science fundamentals and represents a new generation of erosion prediction technology (Foster and Lane, 1987; Lane and Nearing, 1989). Unlike the empirical USLE/RUSLE approaches, WEPP utilizes storm event runoff rates and a steady-state sediment continuity equation (Eq.[1]) to simulate erosion processes (Nearing et al. 1989):

$$dG/dx = D_r + D_i \qquad \text{Eq.[1]}$$

where G is the sediment load (kg $m^{-1}s^{-1}$), x is the distance downslope (m), D_r is the rill detachment or deposition rate (kg m^{-2} s^{-1}), and D_i is the interrill sediment delivery rate to rills (kg m^{-2} s^{-1}).

Net soil detachment in rills is calculated when the flow hydraulic shear stress (τ) exceeds the soil's critical shear stress (τ_{cr}) and the sediment load is below transport capacity (Foster et al. 1995). The rill detachment capacity (D_c) is expressed as (Eq.[2]):

$$D_c = K_r(\tau - \tau_{cr}) \qquad \text{Eq.[2]}$$

where D_c is the rill detachment capacity rate (kg m^{-2} s^{-1}); Kr is the rill erodibility (kg m^{-2} s^{-1}); τ is the flow shear stress (Pa), and τ_{cr} is the critical flow shear stress (Pa) (Foster et al. 1995). Flow shear stress was obtained with Eq. [3].

$$\tau = \gamma R_h S \qquad \text{Eq.[3]}$$

where γ is the specific weight of water (N m^{-3}); R_h is the hydraulic radius of the flow (m); and S is the slope gradient of the rill channel (m m^{-1}).

Briefly, rill erodibility (K_r) is a measure of soil susceptibility to detachment by concentrated flow, and is often defined as the increase in soil detachment per unit increase in shear stress of clear water flow. Critical shear stress (τ_{cr}) is an important term in the rill detachment equation, and is the shear stress below which no soil detachment occurs. Critical shear stress (τ_{cr}) is the shear intercept on a plot of detachment by clear water vs. shear stress in rills. Thus, the relationship between detachment rate (D_c) and flow shear stress (τ) is used to determine soil erodibility parameters. The slope of the regression line corresponds to rill erodibility (K_r), whereas the x-intercept gives the critical shear stress (τ_{cr}). Accordingly:

- **Rill erosion (detachment)** occurs if $\tau > \tau_{cr}$ and sediment supply ≤ transport capacity.
- **Deposition** occurs if sediment supply > transport capacity.
- **No erosion** occurs if $\tau \leq \tau_{cr}$.

Transport capacity in WEPP model depends on flow depth, velocity, slope, and soil erodibility. In practice, rill erodibility parameters (K_r and τ_{cr}) may be determined from laboratory or field flume experiments, or estimated through default regression equations embedded in the WEPP model. These equations were developed from extensive USDA-ARS experimental datasets, allowing estimation when direct measurements are unavailable (Alberts et al. 1995; Flanagan and Livingston, 1995). For freshly tilled cropland surface soils with no residue or root effects, the equations are given as follows:

For soils with ≥30% sand:

$$K_r = .00197 + .00030VFS + .03863e^{-1.84OM} \quad \text{Eq.[4]}$$

$$\tau_{cr} = 2.67 + 0.065C - 0.058VFS \quad \text{Eq.[5]}$$

For soils with <30% sand:

$$K_r = .0069 + .134e^{-.20C} \quad \text{Eq.[6]}$$

$$\tau_{cr} = 3.5 \quad \text{Eq.[7]}$$

where VFS is the very fine sand content (%), C is the clay content (%), and OM is the soil organic matter content (%). The VFS value must be less than or equal to 40%, and if it is greater than 40%, it is assumed to be 40% in this equation application. The OM must be greater than 0.35%, and if it is less than 0.35%, it is set at 0.35%. C must be greater than 10% and less than 40%, and if it is less than 10%, it is set at 10%, and if it is greater than 40%, it is set to be 40%. If measured values fall outside these ranges, default thresholds are applied as recommended in the WEPP model documentation.

Although these parameter estimation equations are widely applied, their predictive accuracy can vary considerably across soils with different textures, initial soil moisture conditions, and slope gradients. For this reason, the present work emphasizes a comparative evaluation of parameterization approaches and their implications for rill erosion prediction under diverse soil and landscape settings.

Results and Discussions

Key Insights and Limitations of the WEPP Model for Predicting Rill Erodibility and Critical Shear Stress in mini-flume experiments

The evaluation of WEPP default equations against mini-flume measurements (Devien Saygın et al. 2018; Ari et al. 2025; Aksouh et al. 2025) revealed low levels of agreement, particularly for critical shear stress (τ_{cr}). While rill erodibility (K_r) estimates were closer to observed values in coarse texture soils with some clay soils, τ_{cr} values were consistently overestimated. This discrepancy largely reflects differences in initial moisture conditions (drained vs. dry vs. saturated), the scale mismatch between controlled laboratory flumes and field rills, and differences in aggregate size and stability. The baseline equations of WEPP were originally developed on croplands with slopes ranging from 3% to 6% (Nearing et al. 1989; Foster et al. 1995), conditions that may not adequately capture variability in finer laboratory settings or steeper experimental slopes.

These findings are consistent with those reported by Elliot and Flanagan (2023), who revisited WEPP parameter estimation through an extensive regression analysis on cropland soils. Their results indicated that:

- Very fine sand content is the dominant predictor of rill and interrill erodibility.
- Slope steepness is the most important factor for predicting τ_{cr}.
- The most reliable equations include both soil texture and mineralogical terms, particularly clay mineralogy, organic carbon, and cation exchange capacity.
- Equations developed without considering carbonate content tend to overpredict erodibility in $CaCO_3$-rich soils. In fact, of the 36 soils used to develop WEPP's original equations, only three contained high calcium carbonate levels, leaving a significant knowledge gap for calcareous soils.

In these earlier mini-flume experiments, Nash–Sutcliffe efficiencies (NSE) showed that K_r predictions were acceptable, particularly in coarse textured soil types, whereas τ_{cr} values showed poor performance, compared to original field-scaled simulations. The WEPP Hillslope tool accounts for slope in hydraulic computations but assumes a fixed τ_{cr} regardless of gradient, a simplification that may not hold for steeper conditions. Indeed, comparison of different slope gradients (3, 7, and 10%) indicated that stream power (ω) outperformed shear stress (τ) in predicting rill detachment, yielding higher R^2 values under steep slopes (Figure 1-3). This suggests that a shift from τ-based to ω-based formulations may improve WEPP's ability to capture the dynamic hydraulic forces driving erosion in complex terrains.

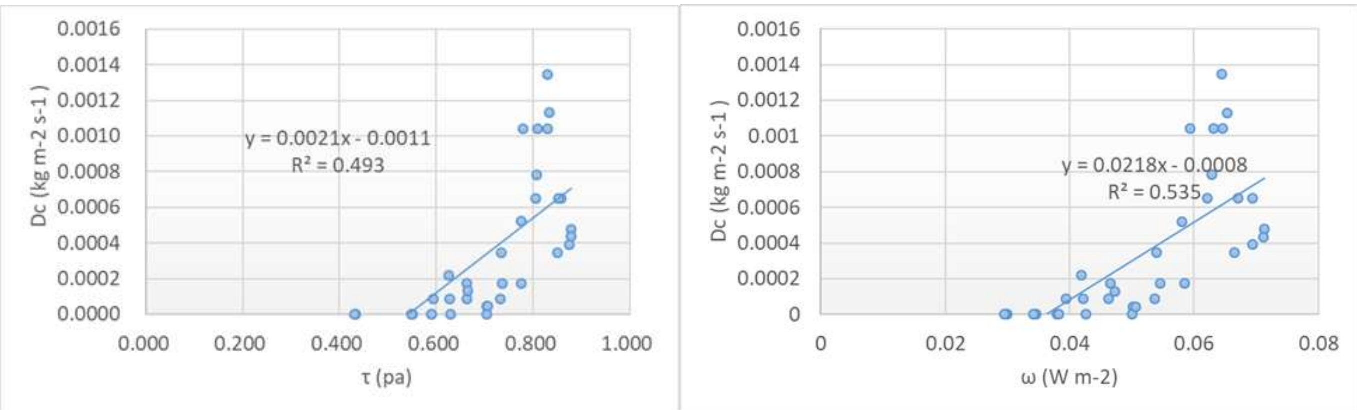

Figure 1. Comparison of Stream Power and Flow Shear Stress for Sandy Loam Soil at 3% Slope

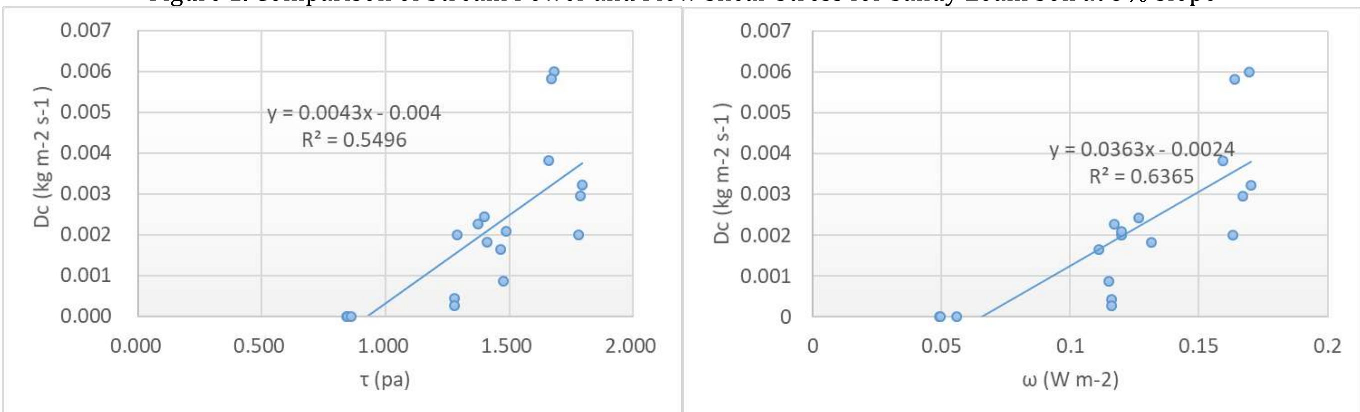

Figure 2. Comparison of Stream Power and Flow Shear Stress for Sandy Loam Soil at 7% Slope

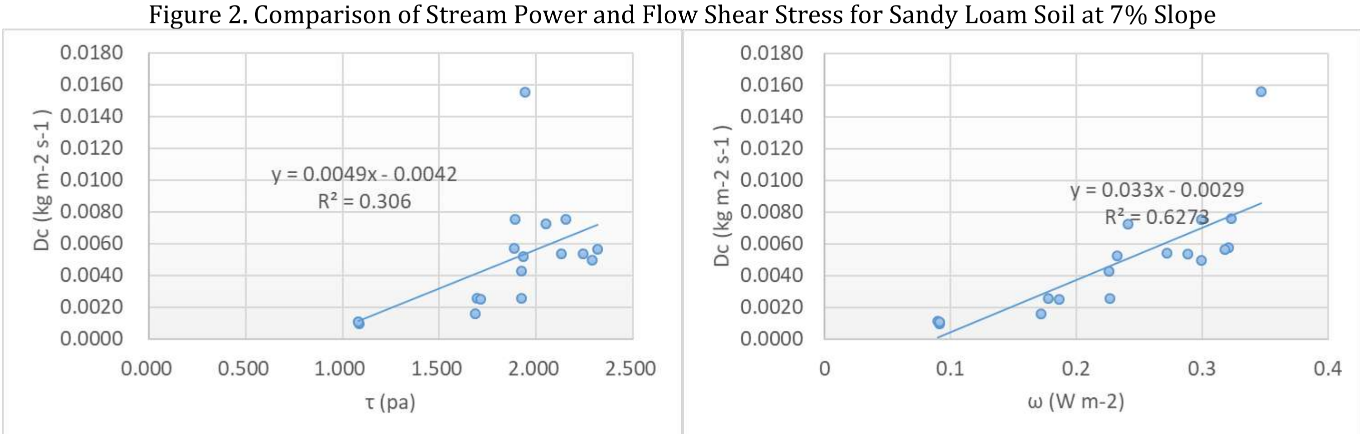

Figure 3. Comparison of Stream Power and Flow Shear Stress for Sandy Loam Soil at 10% Slope

Overall, the synthesis of experimental results and recent model refinements underscores several limitations of default WEPP equations:

1. Initial soil moisture conditions exert strong controls on rill detachment, yet are not explicitly incorporated into default parameterizations.
2. Slope effects are underestimated in τ_{cr} predictions, limiting reliability in steeper landscapes.
3. Soil carbonate content remains underrepresented in current parameterizations, leading to systematic overprediction for calcareous soils.

Future efforts should therefore integrate stream power formulations, expand parameter databases to include calcareous and carbonate-rich soils, and develop moisture-sensitive functions for K_r and τ_{cr}. Such improvements, building on Elliot and Flanagan (2023) and subsequent studies, would enhance the predictive robustness of WEPP across diverse soil–slope–moisture domains.

Briefly, shear stress remains the primary hydraulic driver in rill erosion, consistent with WEPP's foundational assumptions; however, τ-based predictions diverge under steep slopes, suggesting that stream power (ω) may provide a more accurate representation of rill hydraulics. Default equations for rill erodibility show considerable uncertainty, particularly in structured or calcareous soils, highlighting the need for further research on soils with distinctive chemical or physical properties. Incorporating factors such as clay mineralogy, organic carbon, cation exchange capacity, slope, and additional soil fractions could enhance WEPP's predictive accuracy and reliability. Despite these limitations, process-based models like WEPP hold promise for gradually replacing empirical approaches, provided that site-specific calibration and expanded datasets become available.

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Self-similarity in spatial variability of saturated hydraulic conductivity as affected by soil horizonation

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Abstract

Background: Spatial variation of soil saturated hydraulic conductivity (Ks) in layered soils is highly complex. Understanding this complexity is crucial for ecological, hydrological, and natural resource planning studies. This study aimed to characterize self-similarity in the spatial structure of Ks in vertical and horizontal directions using fractal dimension (D) on an 80-hectare cultivated semi-arid hillslopes of Gypsic Haplustepts and Gypsic Ustorthents in north-central Anatolia, Türkiye. Saturated hydraulic conductivity was measured with a Guelph permeameter at 174 sites in A and C horizons and 138 sites in B horizon. The spatial variation of Ks in the A, B, and C horizons was modeled using semivariograms, and fractal dimension (D) was calculated from the slope of regression lines. Differences in means and D of horizon-specific Ks-values were tested using ANOVA and the method of homogeneity of slopes, respectively. Ks-values ranged from 0.01 to 7.11 cm h-1. The mean Ks value in the B horizon (KsB) was significantly lower than those in the A horizon (KsA) and the C horizon (KsC) at the 0.01 significance level. Semivariograms were highly different between the soil horizons in nugget, sill, and range. KsA and KsC were described with exponential models, and KsB with a Gaussian model. The calculated D-values ranged from 2.641 in the B to 2.96 in the A horizon. D-value for KsB was significantly lower than those for KsA and KsC, whereas KsA and KsC showed homogeneity at the 0.01 significance level. All three horizons exhibited D-values greater than 2.50, indicating that the spatial structure of Ks was anti-persistent in all three horizons. These findings suggest that soil horizonation can lead to significantly different self-similar spatial patterns of Ks, and that fractal geometry is useful for statistically distinguishing this aspect of Ks spatial data.

Keywords: Fractal dimension, persistence, self-similarity, soil horizonation, spatial structure

Introduction

Saturated hydraulic conductivity (Ks) is one of the most spatially variable soil properties as it is controlled by the interaction of numerous static and dynamic soil attributes (Sobieraj et al., 2004). Soil horizonation fundamentally affect Ks (Schaetzl and Anderson, 2005). According to Bouma et al. (2011), even very similar soil horizons may have highly different hydrological properties, including Ks, due to variations in soil development and in interrelation between Ks and soil parametric and morphometric variables. Differences in soil formation factors and processes lead to varying morphological and parametric properties of soil horizons. These differences directly influence the extent and variability of hydraulic conductivity in near saturated and saturated conditions (Karahan and Erşahin, 2017). Therefore, complex spatial pattern of Ks in layered soils

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resulted from a combination of vertical and horizontal variability (Schaetzl and Anderson, 2005), necessitates consideration of horizon-specific Ks values-in studies related to soil water management, ecological modeling, and environmental quality.

Fractal analysis has been widely used to characterize spatial complexity of land processes (Chi et al., 2012). Fractal geometry describes soil spatial variability across a range of scales and helps identify self-similarity or self-affinity, which are fundamental characteristics of fractal objects and central concepts in fractal geometry (Xu et al., 1993; Vidal Legaz et al., 2017). Self-similar objects exhibit identical transformations in all directions of Euclidean coordinate space, while self-affine objects exhibit different transformations in each direction (Mandelbrot, 1882; Xu et al., 1993). Self-affinity is more common in fractal analysis of landscapes (Burrough, 1983; Xu et al., 1993).

Fractal dimension serves as a predictor of the scaling regularity in irregular behaviors including geostatistical variations, thereby linking them to fractals (Burrough 1983; Webster, 2008). A surface with a higher D is more disordered over short distances and shows smaller variability over long distances (Bellehumeur and Legendre, 1998; Perez et al., 2010; Chi et al., 2012). Conversely, a small D indicates domination of long-range effects (Burrough, 1981; Phillips, 1985). Fractal dimensions of one-dimensional data for soil and other environmental variables are mainly close to 2 (Palmer, 1988). For two-dimensional data, a fractal dimension <2.5 indicates persistence, and one >2.5 indicates anti-persistence (Vidal Vázquez et al., 2005). A persistent surface shows positive spatial correlation, while an anti-persistent surface shows the reverse between point data. A D-value of 2.5 is generally taken as a reference, representing physical processes characterized by well-known Brownian motion (Vidal Vázquez et al., 2005). Spatial fractal analysis, combined with geostatistics, has enhanced our understanding of soil spatial variability (Perez et al., 2010). In fractal analysis, the principal issue is explaining the information comprised in D, i.e., interpreting the physical significance of D (Xu et al., 1993).

Spatial structure of a soil variable is widely characterized by semivariogram and its parameters (nugget, sill, range, and model type). However, those parameters give no direct evaluation about self-similarity or self-affinity in the spatial structure of variables across scales. In this study, we hypothesized that the spatial self-affinity/self-similarity of Ks will differ in the A, B, and C horizons as characteristics of these horizons are differently affected by soil forming processes and factors. The research objectives were to characterize self-similarity in spatial structure of Ks in the A, B, and C horizons by fractal analysis, and discriminate the D values for A, B, and C horizons by slope test of D.

Material and Methods

Study Area

Detailed information on materials and methods of this study is given in previously published two papers (Kavaklıgil and Erşahin, 2023 a,b). The study area, situated in north central Anatolia, Türkiye (Figure 1), encompasses approximately 80 hectares of cultivated hillslopes. These hillslopes consist predominantly of typical features including topslope, shoulder, backslope, footslope, and toeslope (Schoeneberger et al., 2012). Climate in the study area is the "dry-subhumid/semi-arid continental Anatolia" (Iyigun et al., 2013). The long-term mean annual precipitation in the area ranges from 406.0 to 538.0 mm, with mean annual temperatures between 9.1°C and 11.1°C, and mean relative humidity varying from 61.0% to 66.0%. The average minimum temperature ranges from −5.0°C to −2.7°C in January, while the average maximum temperature ranges from 26.4°C to 30.9°C in July. Recorded temperature extremes include a low of −24.0°C in January and a high of 42.0°C in July.

The soils of the study area are classified as Fluventic Xerorchepts and Fluventic Xerorchents according to Soil Taxonomy (Soil Survey Staff, 2014). The study area's parent material varies by slope position: on most steeper sites it is a mix of gypsum and calcium carbonate with colluvium over lacustrine residuum; on other slopes it is loose, ash-like unconsolidated deposits over lacustrine residuum; and on flat to gently sloping areas it is gypsum over lacustrine residuum. Soils on backslope, footslope, toeslope, and in depressions typically exhibit A–B–C horizons (primarily A–Bw–C) and are classified as Fluventic Xerorchepts. On some eroded shoulders, soils with A–C profiles are classified as Fluventic Xerorchents. No hydromorphic features, salinity, or alkalinity were observed. The entire area has been under conventional wheat tillage for more than 70 years (Kavaklıgil and Erşahin, 2023b).

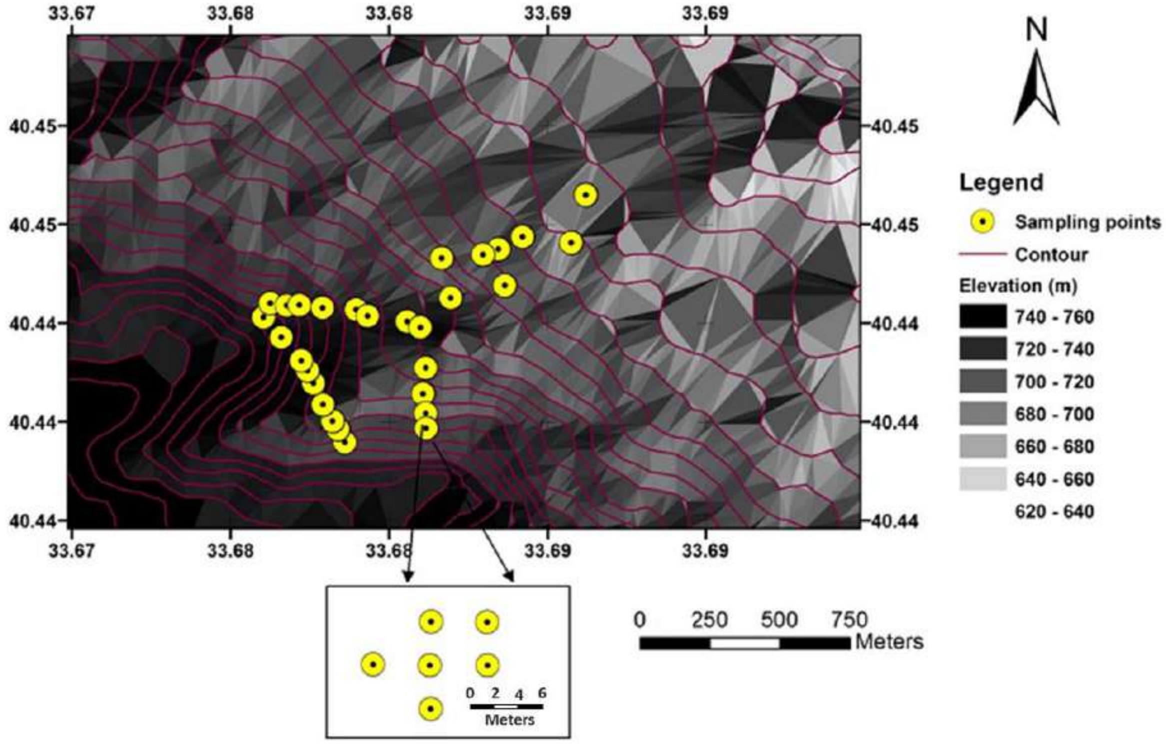

Figure 1. Location of soil profiles in the study area (Kavaklıgil and Erşahin 2023b). The dots on the map indicate the locations of the soil profiles. In the enlarged rectangle, the central dot represents the soil profile itself, while the surrounding dots show the sites where soil samples were collected and saturated hydraulic conductivity (Ks) measurements were taken in proximity to the profile.

Soil Sampling and Analysis

In total, we excavated 29 soil profiles at summit, shoulder, backslope, footslope, and toeslope positions on hillslopes with varying aspects (Figure 1) and described them according to Soil Taxonomy (Soil Survey Staff, 2014). Sampling was carried out by horizon. To increase the number of depth-matched pairs for shorter lags, five additional sampling points were established at the same horizon depths adjacent to each of the 29 soil profiles (Fig. 1). Surface horizons were collected with a shovel, while deeper horizons were accessed using an auger. Undisturbed samples for bulk density and field-capacity determinations were obtained exclusively from the profiles using 100 cm^3 steel cylinders. Disturbed samples were gathered both from the profiles and from the nearby auxiliary sampling points. All sampling—disturbed and undisturbed—took place during soil-profile description, and every location (including the adjacent points) was recorded with GPS coordinates.

Disturbed soil samples were taken to the laboratory and analyzed for basic soil properties, including sand, silt, and clay content (Gee and Bauder, 1986); aggregate stability index (Kemper and Rosenau, 1986); wilting point (Klute and Dirksen, 1986); pH and electrical conductivity (McLean, 1982); soil organic matter content (Nelson and Sommers, 1982); cation exchange capacity (Rhoades, 1982); and CaCO3 content (Nelson, 1982). Field capacity (Cassel and Nielsen, 1986) and bulk density (Blake and Hartge, 1986) were measured on undisturbed soil samples.

During sampling, saturated hydraulic conductivity (Ks) was measured in the field using a Guelph permeameter. At each of the 29 soil profiles, six measurements were taken at adjacent points and at depths corresponding to the vertical midpoint of each horizon (Figure 1). The vertical midpoint of each horizon served as the representative depth for both soil sampling and Ks determination. We followed the procedure specified in the relevant standard method provided by Log (2008) in measurement and calculation of Ks. We excavated a clear cylindrical well with 10-cm diameter with an auger to desired depth, established 5 cm water head at the bottom of the borehole and monitored rate of fall of the water surface in the reservoir until steady-state falling rate is reached, and recorded the water level at every 30 seconds and continued until difference between five consecutive measurements were negligible.

Some eroded sites exhibited only A and C horizons; at those locations, both soil sampling and Ks measurements were made at two depths, corresponding to the A and C horizons. At all other sites, sampling and measurements were conducted at three depths (A, B, and C horizons). In total, this resulted in 486 soil samples—174 from A, 138 from B, and 174 from C horizons—and 486 corresponding Ks measurements.

Calculation of Fractal Dimension for K_s

A semivarivariance (γ) for a specified lag distance (h) is calculated by Eq. (1) (Isaaks and Srivastava, 1989):

$$\gamma(h) = \frac{1}{2\,N(h)} \sum Z(x) - Z(x+h)^2 \qquad (1)$$

Where, *N(h)* is the number of pairs of data points separated by a distance corresponding to the h, Z (x) is the observed value of the variable at the location x and Z ($x+h$) is the observed value of the same variable at $x+h$.

The fractal dimension for a one-dimensional transect can be calculated by Eq. (2) (Burrough, 1983; Bellehumeur and Legendre, 1998; Webster, 2008; Paterson et al., 2018).

$$D = 2 - m/2\,. \qquad (2)$$

Where, m is the absolute slope of log-log plot of $\gamma(h)$ against h. For a two dimensional isotropic Brownian surface. The Eq. (2) becomes (Burrough, 1983; Xu et al., 1993; Bellehumeur and Legendre, 1998; Eghball et al., 1999; Vidal Vázquez et al., 2005; Paterson et al., 2018):

$$D = 3 - m/2\,. \qquad (3)$$

To calculate D, first we calculated semivariances (γ (h) by Eq. (1) then we regressed log $\gamma(h)$ against corresponding values of log h and calculated m and D. As all semivariograms were isotropic, following Paterson et al. (2018), all the D-values were calculated by Eq.(3) and discussion of fractality of Ks was based on the two dimensional D-values.

We calculated isotropic semivariograms for Ks in A (KsA), in B (KsB), and in C (KsC) horizon. We tried different lag distances to obtain the most proper lagging, yielding strongest signal of fractality besides most proper curve fitting (based on greatest coefficient of variation and lowest residual sum of squared error).

Fractal dimensions (D) were calculated for KsA, KsB, and KsC datasets, considering values with the highest coefficient of determination (R^2) and lowest sum of squared residuals (SSE) (Cambardella et al., 1994). Lag distances of 1, 2, 3, 5, 100, 200, 300, and 400 m resulted in the highest R^2 and lowest SSE in all three horizons. A minimum of seven lags was used conveniently in semivariogram modeling and corresponding fractal analysis. Semivariograms were modeled and D-values calculated using GS+ software (Robertson, 2008).

Statistical Analysis

We calculated descriptive statistics including mean, standard deviation, maximum value, minimum value, coefficient of variation, skewness, and kurtosis for the soil properties of the horizons. A one-way analysis of variance (ANOVA) was conducted to determine if there were significant differences among the means of Ks in A, B, and C horizon at a significance level of 0.05. Subsequently, the least significant difference (LSD) technique was used to group the means for Ks (Ott, 1993). Correlation between soil properties and Ks was evaluated by Spearman's correlation analysis.

Since the slope of D-values are related by the corresponding slope of regression line between log lag vs. log semivariance, differences between the slopes can be used to discriminate D-values of the horizons (Eghball and Gary, 1997; Eghball et al., 1999). Therefore, to infer differences between D-values of A, B, and C horizons we simply tested slope of corresponding regression lines using the procedure explained in Kleinbaum et al. (1988). Significance level of 0.05 was considered in all statistical tests.

Results and Discussion

Saturated Hydraulic Conductivity of Soil Horizons

This paper reports part of the data from Ph.D dissertation of the first author. Detailed information on the basic soil properties has been given in previously published two papers (Kavaklıgil and Erşahin 2023 a,b). Therefore, here only brief information will be given on the basic soil data.

Saturated hydraulic conductivity (Ks) was strongly right-skewed according to Webster (2001) and exhibited high variability (Mulla and McBratney, 2002) in all three horizons. According to Webster (2001) a distribution < $|0.5|$ is deemed slightly skewed and assumed normally distributed, a distribution > $|1.0|$ is deemed strongly skewed and log-transformation may be needed to achieve a normal-like distribution. Application of log-transformation resulted in skewness decreased from 2.42 to -0.48 in A, from 1.18 to 0.26 in B, and from 1.98 to -0.33 in C horizon (Table 1). Therefore, we used log-transformed values of K_s in ANOVA and following LSD tests. The mean of K_s-values was significantly lower ($P<0.01$) in the B horizon (KsB) compared to the A (KsA) and the C horizon (KsC). In contrast, the means for KsA and KsC were not significantly different (Table 1).

Table 1. Descriptive statistics for Ks in A, B, and C horizon.

Parameter	Soil horizon		
	A	B	C
Mean	2.58[a]	1.47[b]	2.43[a]
Minimum	0.05	0.01	0.14
Maximum	14.1	12.10	13.50
Standard deviation	7.11	3.40	6.11
Coefficient of variation	103.30	125.50	101.80
Skewness	2.42 (-0.48)#	1.18 (0.26)#	1.98 (-0.33)#
Kurtosis	6.45 (1.01)#	0.16 (0.02)#	4.60 (-0.54)#

Means labelled with the different letters are significantly different at 0.05 level of significance
#: Values in the parentheses represent the log-transformed values

Table 2 shows results of Spearman's correlation analysis conducted between some soil properties and Ks in soil horizons. The soil texture significantly influenced Ks. Soil texture components were correlated with Ks highly differently across the horizons. Silt content influenced K_s positively in A and B horizons and negatively in C horizon, and clay content affected Ks negatively in the A and B horizons, while sand content influenced it only in the C horizon. Lime ($CaCO_3$) content notably had a significantly negative effect on Ks in the A and B horizons. Greater number of soil properties were significantly correlated with Ks in the A horizon.

Table 2. Results of Spearman's correlation analysis between Ks and some soil variables in A, B, and C horizon.

Horizons	Variables									
	Sand	Silt	Clay	FC†	WP	BD	OM	EC	pH	$CaCO_3$
A	0.02#	0.43	–0.37	0.21	0.16	–0.09	–0.21	–0.18	0.25	–0.28
	0.792&	0.0001	0.0001	0.0052	0.034	0.335	0.0052	0.017	0.0008	0.0002
B	0.12	0.16	–0.19	0.19	0.18	–0.09	–0.02	0.06	0.13	–0.38
	0.113	0.034	0.012	0.012	0.017	0.335	0.792	0.428	0.086	<0.0001
C	0.32	–0.15	–0.11	0.01	0.18	–0.16	–0.35	0.37	–0.08	0.11
	<0.0001	0.045	0.146	0.895	0.017	0.034	<0.0001	<0.0001	0.191	0.146

† FC: Field capacity (%), WP: Wilting point (%), OM: Organic matter (%), EC: Electrical condcutivity (dS m^{-1})
#: Correlation coefficient
&: Level of signifance (P)

Spatial Structure of K_s in Soil Horizons

Semivariograms of Ks in the A, B, and C horizons are shown in Figure 2, with their parameters detailed in Table 3. According to Cambardella et al. (1994), who defined spatial dependency based on the nugget ratio (<25% indicating strong, 25-75% moderate, and >75% weak spatial dependency), Ks exhibited strong spatial dependency in the B horizon and moderate spatial dependency in the A and C horizons. The strength of spatial dependency and geostatistical range values varied across horizons, with the spatial dependency ranking as A= C < B and the geostatistical ranges as C < B < A (Table 3). The spatial structure of Ks was isotropic in all three horizons. The exponential model best described the experimental semivariograms for Ks in the A and C horizons, while Gaussian model in the B horizon. These models fit the experimental semivariograms well, as indicated by high coefficient of determination (R^2), and reasonably low sum of squared error (SSE) (Table 3 and Fig. 2).

Table 3. Parameters of semivariograms for Ks in A, B, and C horizons in the study area

Horizon	Model	C_o	C_s	C_o/C_s	Ao	R^2	RSS
A	Exponential	0.64	1.28	0.50	868.80	0.86	0.037
B	Gaussian	0.33	1.90	0.17	129.38	0.96	0.19
C	Exponential	0.571	1.43	0.50	14.10	0.74	2.90

C_o: Nugget variance, C_s: Sill, A_{max}: Maximum range A_{min}: Minimum range, R^2: Coefficient of determination, RSS: Residual sum of squares, NA: not applicable.

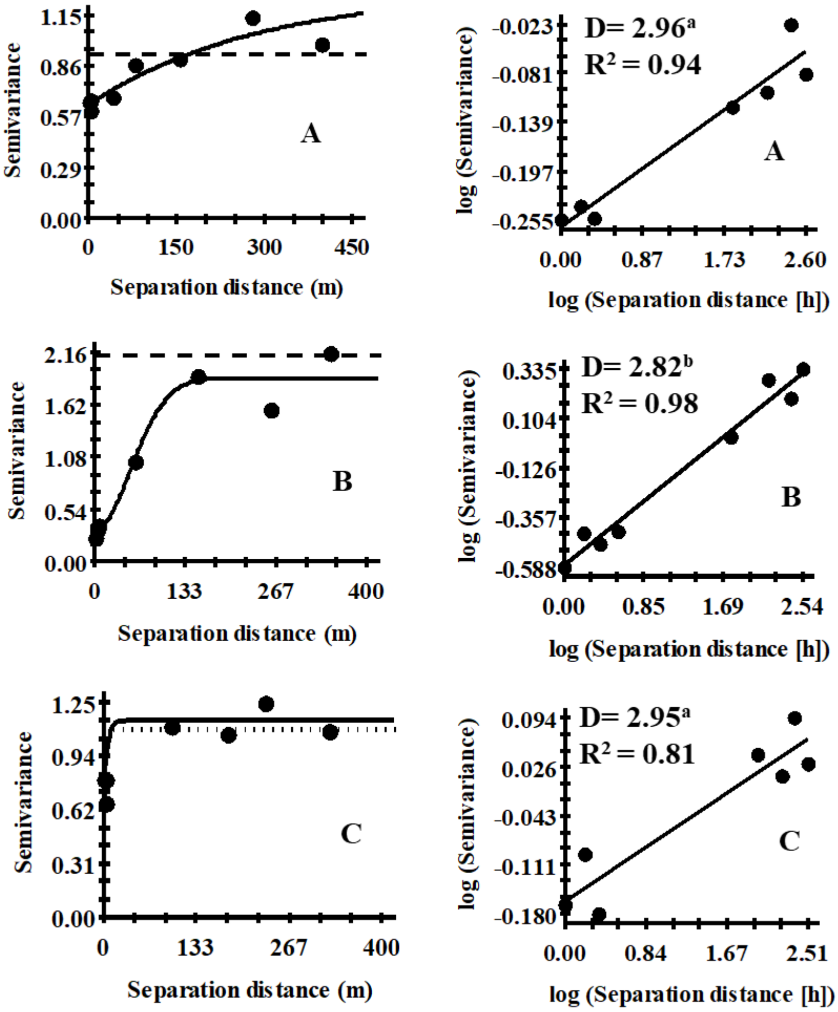

Figure 2. Semivariograms (on the left) and corresponding fractograms (on the right) for K_s in the A, B, and C horizons.

Fractal Dimension of K_s in the Soil Horizons

Fractal dimensions (D) were calculated in A, B and C horizons (Fig. 2). The fractal dimensions of K_sA and K_sC were almost identical in magnitude, with the lowest D-value observed in B and the highest in A. All D-values were between 2.0 and 3.0, indicating that the Ks-data for the two-dimensional isotropic surfaces were self-similar to some extent within the scale of interest. The D-values were modeled successfully, as shown by high coefficient of determinations (Fig. 2). The D-value for the B horizon was significantly lower than those for A and C horizons, while the D-values for A and C horizons were statistically homogenous, as evidenced by the slope tests of the corresponding regression lines (Fig.3).

Conclusion

We studied self-similarity of spatial structure of Ks in A, B, and C horizons of 80-ha semiarid hillslopes, which has been cultivated for wheat for over 70 years. ANOVA and LSD tests revealed that the mean Ks in the B horizon was significantly lower than in the A and C horizons, while the means for Ks in the A and C horizons were statistically homogeneous ($P<0.01$).

The fractal dimension (D) for (Ks) in the B horizon was significantly lower than those in the A and C horizons, indicating a more self-similar spatial variability structure in the B horizon. In all three horizons, the fractal dimension exceeded 2.50, suggesting that the spatial distribution of Ks was anti-persistent, with the A horizon showing the highest degree of anti-persistence. Fractal analysis effectively highlighted differences in the spatial organization of Ks among the soil horizons. The B horizon exhibited distinct spatial characteristics compared to the A and C horizons, including differences in nugget ratio, geostatistical range, model type, and self-similarity. Overall, it can be concluded that the structure and distribution of the B horizon play a critical role in shaping the variability and behavior of Ks-related processes within the study area.

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Comparison of mineral and heavy metal contents in the soils of conventional and organic apple orchards in Erzincan

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Abstract

This study aimed to compare certain physical properties, nutrient elements, and heavy metal contents of soils taken from conventional and organic apple orchards located in Üzümlü district of Erzincan province. In the scope of the study, the soils of conventional and organic apple orchards were also evaluated in terms of soil fertility. For this purpose, soil samples were collected from 0–30 cm and 0–60 cm depths in 5 organic and 5 conventional apple orchards, and the necessary analyses were performed. An evaluation of the soil mineral contents in organic and conventional apple orchards revealed that, with the exception of sodium (Na) and manganese (Mn), the levels of other mineral elements were found to be sufficient to high. In terms of organic matter content, the soils of organic orchards were classified as "good," while those of conventional orchards were rated as "moderate." Both orchard types exhibited non-calcareous and non-saline soil characteristics, and heavy metal concentrations were below detectable limits. These findings indicate that the soils are suitable for agricultural production. Furthermore, conventional orchards showed differences in organic matter, phosphorus (P), and potassium (K) contents compared to organic orchards, whereas no statistically significant differences were observed between the two orchard types for the remaining mineral elements.

Keywords: Organic farming, conventional farming, heavy metal, plant nutrients, soil fertility, Erzincan

Introduction

Soil is considered as one of the basic factors in agricultural production. When the physical, chemical and biological properties of the soil are appropriate, high crop yields and quality products can be obtained. It is well known that soil structures vary regionally and intensive agricultural practices in our country lead to deterioration of soil structures and decrease in agricultural productivity.

Until the mid-20th century, soils and crops were considered organic. However, with the adevent of intensive agricultural practices, there was a significant increase in the use of high-yielding seed varieties and agricultural inputs such as fertilizers and pesticides. Although this change led to higher yields in the short term, it has also resulted in many negative long-term consequences, including increased soil erosion, rising production costs, overexploitation of groundwater resources, soil salinization, environmental pollution, and decreased food quality (Ram, 2003; Kotschi, 2015; Chandini, Kumar, & Prakash, 2019; IPBES, 2019). The main sources of pollution, especially in agricultural soils, include the intensive use of fossil fuels, exhaust emissions from motor vehicles, mining activities, industrial activities, the use of untreated sewage water and sewage

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sludge for agricultural purposes, and the application of chemical fertilizers and pesticides. These sources contribute to heavy metal pollution, which threatens human and plant health by accumulating in air, soil, and water ecosystems (Duffus, 2002).

Organic agriculture is based on sustainable practices such as crop rotation, green manuring, the use of organic wastes, biological pest control, and the limited application of mineral inputs, aiming to protect ecosystem health and biodiversity (Lu et al., 2005; Rong et al., 2005). Organic farming practices improve soil properties over the long term, support sustainable crop productivity, and contribute significantly to the preservation of soil quality. Compared to conventional farming, organic farming has many advantages such as increased soil fertility, yield and product quality, as well as protection from the negative effects of polluting and carcinogenic products in agriculture (Bishnoi and Bhati, 2017).

The aim of this study was to determine the mineral and heavy metal contents of soils in apple orchards managed under conventional and organic farming systems in Erzincan province. The results provide basic information for sustainable management of soils and development of appropriate fertilization strategies. The aim of such regional studies is to contribute to the establishment of soil health databases, development of integrated fertilization strategies and environmental risk analyses.

Material and Methods

This study was conducted in apple orchards where conventional and organic farming practices are applied in Erzincan Province. The province has a continental climate, characterized by cold winters and hot, dry summers. Due to Erzincan's microclimatic conditions, a wide variety of crops can be cultivated in the region.

The study was conducted by collecting soil samples from ten apple orchards, including five conventional and five certified organic orchards, Üzümlü district of Erzincan province. In April, during the leafing and flowering periods of the apple trees, soil samples were taken from two depths (0–30 cm and 30–60 cm). The locations of the sampled gardens are shown in Figure 1. Orange-colored areas represent organic apple orchards (O1, O2, O3, O4, O5), and blue-colored areas represent conventional apple orchards (C1, C2, C3, C4, C5). Soil analyses were carried out in the soil department laboratory of Erciyes University.

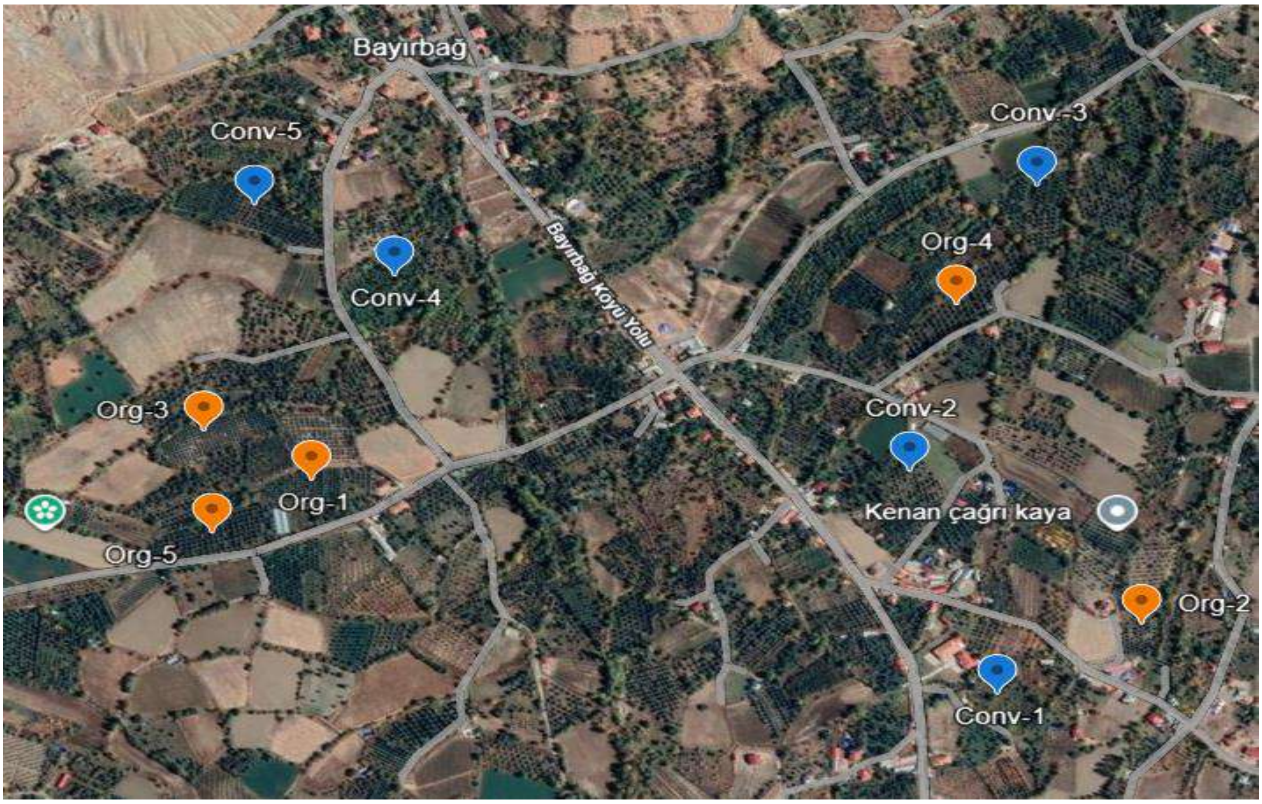

Figure 1. Map of Organic and Conventional Apple Orchard Locations

Some physical and chemical soil properties were determined by using standart soil analyses methods reported by Kacar (2009).The nutrient contents of the harvested plant samples were analyzed in dried and grinded plant samples. The P level was analyzed by the spectrophotometric method, and K, Ca, Mg, Na, micro elements (Fe, Mn, Zn, and Cu) and heavy metals (Al, Ni, S, Cr, Cd, Co, Pb) were determined by using inductively coupled plasma optical emission spectrometry (ICP-OES) (Kaçar, 2009).

Results And Discussion

The soil analysis results obtained from apple orchards under both organic and conventional farming practices in Üzümlü district of Erzincan province are presented in Table 1. In the evaluation of the results, the threshold values proposed by various researchers were taken into account, including soil pH, lime content, organic matter content, and electrical conductivity (EC), phosphorus (Ülgen and Yurtsever, 1995), potassium (Fawzi and El-Fouly, 1980), calcium, sodium, and magnesium (Loue, 1986), as well as microelements such as iron, copper, zinc, and manganese (Lindsay and Norvell, 1978).

According to the analysis results, the soils of the apple orchards under organic farming practices were classified as loamy, whereas those under conventional farming were characterized as sandy and clayey. Soil pH ranged from 7.87 to 8.53 in organically managed orchards and from 7.78 to 8.84 in conventionally managed orchards, indicating that the soils in both systems are slightly alkaline. The average electrical conductivity (EC) values were 0.07 dS m^{-1} for conventional orchards and 0.06 dS m^{-1} for organic orchards. These values indicate that salinity is not a concern in the soils of either farming system.

Analysis of the lime content revealed that soils in the organic farming orchards contained lime levels ranging from 0.80% to 1.44%, whereas those in the conventional farming orchards ranged between 0.80% and 0.96%, indicating that the soils were generally non-calcareous. The average organic matter content was found to be 3.43% in organically managed orchards and 2.93% in conventionally managed orchards. Based on these values, the organic matter content of the soils in organic orchards is considered to be at a good level, while that of the conventional orchards is classified as moderate.

When the phosphorus contents of the soils were examined, it was observed that the phosphorus levels in the soils of organic apple orchards ranged between 7.53 and 26.17 kg/da, generally falling within the medium to very high classification. In contrast, the phosphorus contents of conventional apple orchards varied between 0.78 and 19.59 kg/da and were mostly classified as high to very high.

Table 1. Some Physical and Chemical Properties of Organic and Conventional Orchard Soils

Orchards	Deep (cm)	Texture	pH	EC (dS m^{-1})	Org. Matter (%)	Lime (%)	P_2O_5 (Kg/da)
O1	0-30	Loamy	8,11	0,10	4,28	1,44	21,18
	30-60	Loamy	8,53	0,10	3,93	0,80	26,17
O2	0-30	Loamy	7,96	0,06	4,17	0,96	14,99
	30-60	Loamy	7,87	0,05	3,76	0,96	11,90
O3	0-30	Loamy	8,01	0,05	3,73	0,96	7,53
	30-60	Loamy	7,98	0,06	3,28	0,80	10,39
O4	0-30	Loamy	8,11	0,04	2,61	0,80	8,57
	30-60	Loamy	8,11	0,04	2,77	0,80	9,91
O5	0-30	Loamy	8,20	0,06	2,84	0,96	16,18
	30-60	Loamy	8,13	0,05	2,96	0,80	14,20
	Average		8,10	0,06	3,43	0,93	14,10
	Avr. (0-30)		8,07	0,06	3,52	1,02	13,69
	Avr. (30-60)		8,12	0,05	3,34	0,83	14,51
C1	0-30	Sandy	7,92	0,07	3,01	0,80	14,04
	30-60	Sandy	8,13	0,06	2,95	0,80	14,83
C2	0-30	Sandy	7,91	0,06	3,05	0,80	10,39
	30-60	Sandy	7,95	0,05	2,83	0,80	12,69
C3	0-30	Clay	7,78	0,05	2,84	0,80	1,59
	30-60	Clay	7,97	0,06	3,01	0,80	0,78
C4	0-30	Clay	7,86	0,07	3,15	0,80	19,59
	30-60	Clay	7,93	0,06	3,17	0,80	16,02
C5	0-30	Sandy	8,59	0,08	2,50	0,80	14,44
	30-60	Sandy	8,84	0,07	2,84	0,96	11,50
	Average		8,08	0,06	2,93	0,82	11,59
	Avr. (0-30)		8,01	0,07	2,91	0,80	12,01
	Avr. (30-60)		8,16	0,06	2,96	0,83	11,16

The potassium content of soils from organic apple orchards ranged from 98.91 to 1073 mg kg^{-1}, while in conventional apple orchards it varied between 64.41 and 293.14 mg kg^{-1}. Overall, the potassium levels in organic apple orchard soils were classified as high, whereas those in conventional orchards were considered to be in the medium range. The calcium content of soils in organic orchards ranged from 1518.74 to 2078.63 mg kg^{-1}, and in conventional orchards from 1334.84 to 4885.58 mg kg^{-1}. In general, both organic and conventional apple orchard soils were classified as having moderate calcium levels. Magnesium concentrations ranged from 264.15 to 467.33 mg kg^{-1} in organic orchards and from 363.65 to 527.12 mg kg^{-1} in conventional orchards. These values generally indicate high to very high magnesium levels in both orchard types. Sodium content ranged from 29.18 to 54.57 mg kg^{-1} in organic orchards and from 25.39 to 56.92 mg kg^{-1} in conventional ones, with both being classified as very low to low in sodium content.

Copper levels in organic orchard soils ranged from 4.41 to 27.18 mg kg^{-1}, while in conventional orchards they varied from 3.04 to 12.44 mg kg^{-1}. In general, copper contents in both systems were considered adequate. Iron content ranged from 3.51 to 34.62 mg kg^{-1} in organic orchards and from 2.25 to 15.81 mg kg^{-1} in conventional orchards, both being classified as good. Manganese content was found to range between 2.49 and 5.64 mg kg^{-1} in organic orchards and 2.67 to 4.64 mg kg^{-1} in conventional ones, with both evaluated as very low in manganese. Zinc concentrations ranged from 0.6 to 2.38 mg kg^{-1} in organic orchard soils and from 0.44 to 3.25 mg kg^{-1} in conventional ones, with zinc levels in both orchard types generally considered to be adequate.

Table 2. Comparative analysis of macro and micro nutrient contents in organic and conventional orchard soils

Orchards	Deep (cm)	K	Ca	Mg	Na	Cu	Fe	Mn	Zn
					mg kg^{-1}				
O1	0-30	977	2153,57	438,22	54,57	10,28	29,83	5,64	1,7
	30-60	1073	1580,74	415,39	48,8	10,44	34,62	5,12	1,48
O2	0-30	206,42	1938,1	467,33	31,24	27,18	9,17	4,09	2,38
	30-60	154,2	1518,74	388,57	34,42	20,43	9,08	3,79	1,93
O3	0-30	98,91	1876,73	427,86	31,62	5,75	7,32	2,55	0,94
	30-60	101,17	1646,17	441,43	31,45	6,25	7,89	3,68	1,03
O4	0-30	133,09	1651,77	264,15	29,41	4,41	4,02	3,24	0,6
	30-60	144,65	2078,63	298,31	29,18	4,44	3,84	2,49	0,56
O5	0-30	214,55	1749,3	351,15	30,97	8,53	3,63	3,54	1,21
	30-60	147,35	2024,31	351,42	31,56	6,79	3,51	3,45	0,91
	Average	325,03	1821,8	384,38	35,32	10,45	11,291	3,759	1,274
	Avr.(0-30)	325,99	1873,9	389,74	35,56	11,23	10,794	3,812	1,366
	Avr.(30-60)	324,07	1769,7	379,02	35,08	9,67	11,788	3,706	1,182
C1	0-30	243,99	1790,34	432,66	25,39	5,08	15,81	3,03	0,85
	30-60	293,14	1334,84	363,65	25,82	4,25	13,29	3,22	0,62
C2	0-30	95,93	2188,81	527,12	36,38	12,44	12,57	4,64	1,93
	30-60	64,41	1875,74	468,22	34,88	9,23	13,53	3,6	1,38
C3	0-30	219,2	4885,58	387,67	56,92	3,04	11,84	4,51	0,48
	30-60	181,51	1704,65	399,6	44,25	3,05	10,69	3,82	0,44
C4	0-30	160,8	2502,78	479,14	31,29	6,02	8,53	3,87	3,25
	30-60	166,02	1953,84	515,57	40,87	4,69	8,73	3,56	1,76
C5	0-30	220,26	2960,31	368,51	29,59	6,11	2,25	2,67	1,01
	30-60	157,32	3199,21	391,52	33,03	6,76	2,34	2,85	0,94
	Average	180,258	2439,61	433,366	35,842	6,067	9,958	3,577	11,59
	Avr.(0-30)	188,036	2865,564	439,02	35,914	6,538	10,2	3,744	12,01
	Avr.(30-60)	172,48	2013,656	427,712	35,77	5,596	9,716	3,41	11,16

The concentrations of heavy metals (Lead (Pb), Cadmium (Cd), Chromium (Cr), Cobalt (Co), Nickel (Ni), and Mercury (Hg)) in soils collected from orchards practicing both organic and conventional apple cultivation were analyzed. The evaluation of heavy metal levels in the soils was conducted in accordance with the limit values specified in the Regulation on the Control of Soil Pollution and Contaminated Sites with Point Source Pollution, published by the Ministry of Environment and Urbanization (Anonymous, 2010). The analysis indicates that heavy metal concentrations in both organic and conventional apple orchards are undetectable or fall below permissible regulatory thresholds.

The results revealed that the soils of both organic and conventional apple orchards exhibit alkaline reaction, non-saline, and free lime. The soils of organic apple orchards were generally characterized by loamy texture, adequate levels of organic matter, moderate to high phosphorus content, and high potassium levels. In contrast, the soils of conventional apple orchards exhibited sandy and clayey textures, medium levels of organic matter, high to very high phosphorus content, and moderate potassium levels.

Regarding the nutrient element composition in both production systems, calcium (Ca) content was found to be at a moderate level, magnesium (Mg) content was very high, and sodium (Na) content was generally very low to low. Additionally, copper (Cu) and zinc (Zn) contents were sufficient, iron (Fe) content was at a good level, while manganese (Mn) levels were found to be very low. Furthermore, the analysis of soils from both organic and conventional apple orchards indicated that heavy metal concentrations were below detectable limits and remained well within the threshold values established by national regulations in Turkey.

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Mapping of Soil Nutrients Using GIS for Nutrient Management in Hazelnut

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Abstract

The objective of this study was to determine soil reaction and macronutrient content in Hazelnut soils located in Akçatepe district, Ordu. For this purpose, soil samples were collected from the study area to evaluate the soil fertility parameters. The soil samples were analysed for the following soil properties: soil pH and macronutrients as total N, available P and available K, Ca, Mg. Afterward, soil nutrient maps were prepared by IDW method with the obtained data results. The maps showed the pH of the soils were between 5.30-7.51 indicating slightly acid to neutral and most of the nutrients were at sufficient levels. In this study, obtained maps of the soil macronutrients indicated that total N, available Ca, Mg and K were at sufficient level whereas available P was insufficient. In addition to, soil nutrients in the study area were positively correlated with each other. Soil pH and total N; available P, available K; available Ca are positively correlated. Results showed that, soil nutrients may be mapped to compare nutritional level and make it easy fertilizer application for nutrient management. **Keywords:** Macronutrient, pH, soil, IDW, map

Introduction

Soil fertility is defined as ability of soil to sustain plant growth and provide essential nutrient (Tudi et. al.,2022). Soil nutrient elements such as total nitrogen, available phosphorous and available potassium and soil pH are among the basic parameters for determining soil fertility. In additon to this, the availability of nutrients in soil associated with the soil pH. (Yuan, 1983). Thus, determining pH of the soil and nutrients in soils is an important research in soil fertility.

GIS methods have been used in soil science to determine spatial variability of nutrients in soils (Khadka et. all 2018). GIS application provides methods for specify the spatial distribution of soil properties and based on this, it helps create a fertilizing models. Thus, GIS application has been widely used for studying of soil fertility and fertilization (Tiruneh et. al 2021).

Mapping of the soil nutrients is of considerable importance in hazelnut for nutrient management and fertilization application. It is essential to determine the spatial variability of nutrients in soils and plant nutrients requirement in order to plan site specific fertilizer programme. There are few studies that focus on soil fertility determination for hazelnut in the region.

The objective of this study was to determine soil reaction and macronutrient content in Hazelnut soils and to design a maps of soil nutrients showing the areas that need a fertilization based on soil nutrient level for hazelnut.

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Material and Methods

Study area

The study area has 6.75 da hazelnut orchard, located in, Akçatepe district, Ordu. It is situated at the longitude 411500-411625 East and latitude 4535900-4536000 North (WGS84 UTM Zone 37 North).

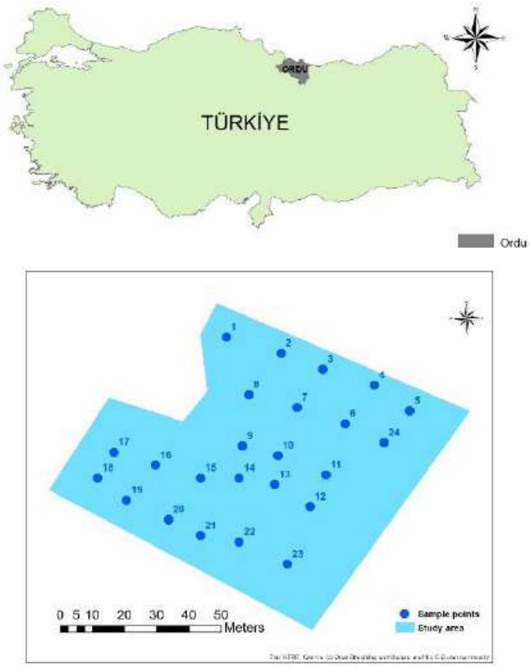

Figure 1. Location of study area and sampling point

Soil sampling and analysis

Twenty-four soil samples were collected at a depth 0–30 cm, in April 2025. The samples were taken randomly (Fig. 1) and the sampling positions were geo-referenced using a GPS. The random sampling was taken before fertilization.

The soil samples were dried in the shade at room temperature and passed through a 2 mm sieve and analysed for the following properties: soil pH, total N, available P, available Ca, available K, available Mg. Soil pH was determined using a pH meter at a soil:water ratio (1:2.5 w:v) (Richards, 1954). Soil total N was determined by Kjeldahl method (Bremner 1965). Available P were determined by Bray Kurtz through spectrophotometry (Kacar, 2009). Available Ca, Mg and K were extracted using neutral normal ammonium acetate solution (NH_4OAc–K) and were determined on an AAS (Kacar, 2009).

Mapping model

Maps of spatial distribution of soil fertility parameters were prepared in Arc GIS 10.5 software using the inverse distance weighted (IDW) interpolation method (Tiruneh et. al. 2021).

Statistical Analysis

Descriptive statistic of soil data parameters (min, max., mean, standard deviation, coefficient of variation, skewness and kurtosis) were performed using Minitab 20. Pearson correlation was used as an indicator to detect relationships between soil fertility parameters. Significant differences were determined by Pearson least significant difference (LSD) test ($p < 0.05$).

Results and Discussion

Descriptive statistics of soil fertility parameters

Descriptive statistic of soil data such as minimum, maximum., mean, standard deviation, coefficient of variation, skewness and kurtosis are presented in Table 1. The soil fertility parameters in the study area were selected as soil pH, total N, available P, K, Ca and Mg The coefficient of variation were calculated to examine the variability of soil fertility parameters using the following order ≤25 low variations; >25 ≤50 moderate variations and >50 high variations (Khadka et al.2018). The results showed highest variability in coefficients of variation in soil phosphorous and lowest variability in coefficients of variation in soil pH. In addition to, the coefficient of variation was low for soil total N, available Ca and Mg.

Table 1. Descriptive statistics of the soil fertility parameters in the study area

Properties	Mean	StDev	CV	Min	Max	Skewness	Kurtosis
pH	6.06	0.572	9.44	5.30	7.52	1.04	0.50
N, %	0.23	0.044	19.31	0.155	0.30	0.14	-1.12
P, mg kg^{-1}	4.18	4.121	98.59	0.59	19.35	2.39	7.42
K, mg kg^{-1}	282.2	112.2	39.77	142.6	507.4	0.32	-1.13
Ca, mg kg^{-1}	3258	794	24.36	1294	4944	-0.19	0.91
Mg, mg kg^{-1}	471.2	96.1	20.39	215.7	590.1	-1.35	1.09

Pearson correlation relations

Pearson correlation coefficients between data of soil fertility parameters are presented in Table 2. The soil nutrients in the study area were positively correlated with each other Significant relationship was found between soil pH and total N (r = 0.422, p<0.05); available P (r = 0.499, p<0.05), available K (r = 0.824, p<0.01), available Ca (r = 0.448, p<0.05). In this study, there were no significant relationship between soil pH and soil available magnesium**.** In addition to, positive relationship was found between soil total N and soil available Ca (p< 0.01) and Mg (p<0.05); soil available P and soil available K (p< 0.01); soil available Ca and Mg (p< 0.01).

Table 2. Correlation between soil fertility properties

	pH	N	P	K	Ca
N	0.422*				
P	0.499*	-0.090			
K	0.824**	0.148	0.660**		
Ca	0.448*	0.841**	0.061	0.259	
Mg	0.058	0.460*	0.047	0.160	0.606**

Classification of limit values for soil properties

The classification of the limit values for selected soil properties are presented in Table 3. These limit values were used for preparing soil maps.

Table 3. Classification of limit values for selected soil properties

Property	Interpretation Classes						References
	Very low	Low	Adequate	High	Very high		
N %	<0.045	0.045-0.090	0.090-0.170	0.170-0.320	>0.320		Sillanpää, 1990
P, mg kg^{-1}	<2.5	2.5-8.0	8.0-25	25-80	>80		Sillanpää, 1990
K, mg kg^{-1}	<50	50-110	110-290	290-1000	>1000		Sillanpää, 1990
Ca, mg kg^{-1}	<238	238-1150	1150-3500	3500-10000	>10000		Sillanpää, 1990
Mg, mg kg^{-1}	<50	50-160	160-480	480-1500	>1500		Sillanpää, 1990
pH	Strongly acidic <4.5	Moderately acidic 4.5-5.5	Slightly acidic 5.5-6.5	Neutral 6.5-7.5	Slightly Alkaline 7.5-8.5	Strongly Alkaline >8.5	Richards, 1954

Mapping of soil pH and macro nutrients

The spatial distributions maps of the soil pH and macronutrients in the study area are given in Figure 2, 3 and Figure 4.

The soil pH of the study site ranges from 5.30 to 7.52, varied from moderately acid to slightly alkaline. In addition, the map of soil pH showed most of the soils in the study site was slightly acidic (Fig. 1). In this study, soil pH was suitable for availability of nutrients. Thus, it cannot restrict the availability of soil nutrients and obtained results showed that soil pH and soil nutrients such as total N, available P, K, Ca, had a positive relation to each other.

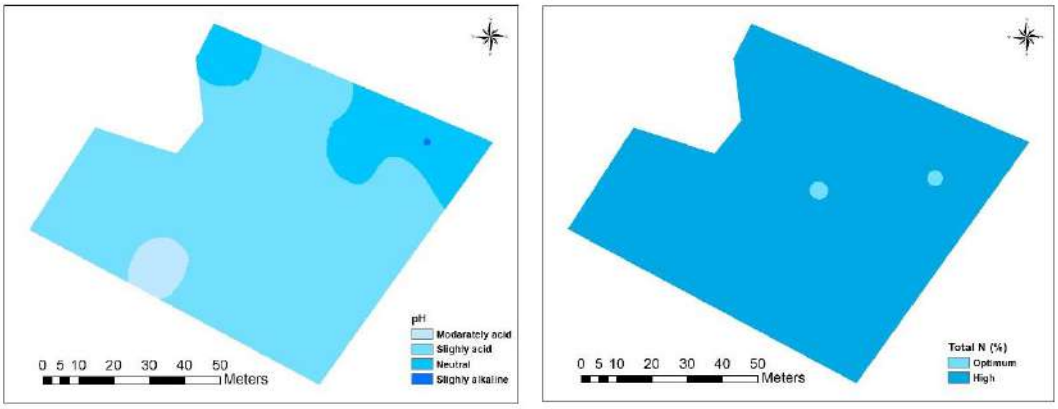

Figure 2. Map of soil pH and total nitrogen

The total nitrogen values were between 0.15 and 0.30 % with the mean of 0.23 %. The total nitrogen content in the soils was adequate and high. The map of total nitrogen showed that most of study side had high total nitrogen content.

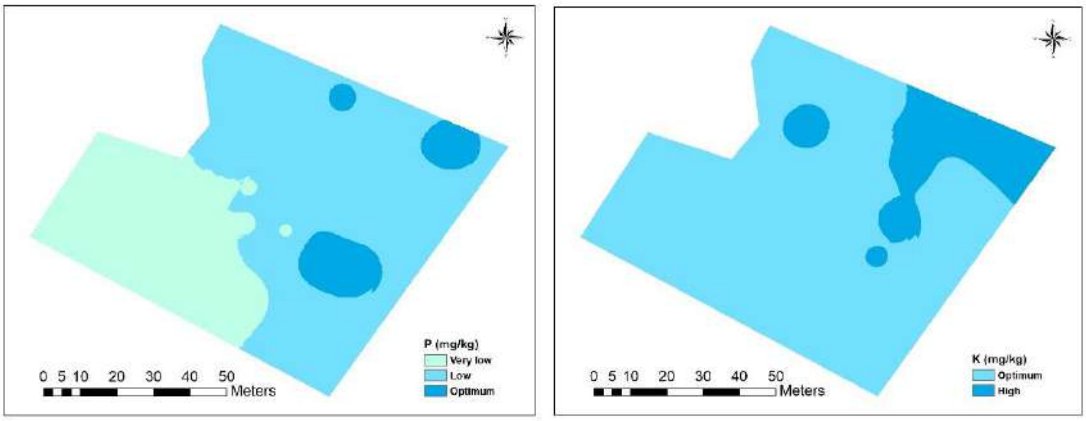

Figure 3. Map of available P and K

The available P content in the soils were between 0.59 and 19.35 mg kg^{-1} with the mean of 4.18 mg kg^{-1}. The map indicated that the available phosphorus varied from very low to adequate level. The map of available phosphorus shows that the most of the study area was insufficient in available phosphorus (Figure 3). It might be due to phosphorus fertilizer hasn't been applied to the study site.

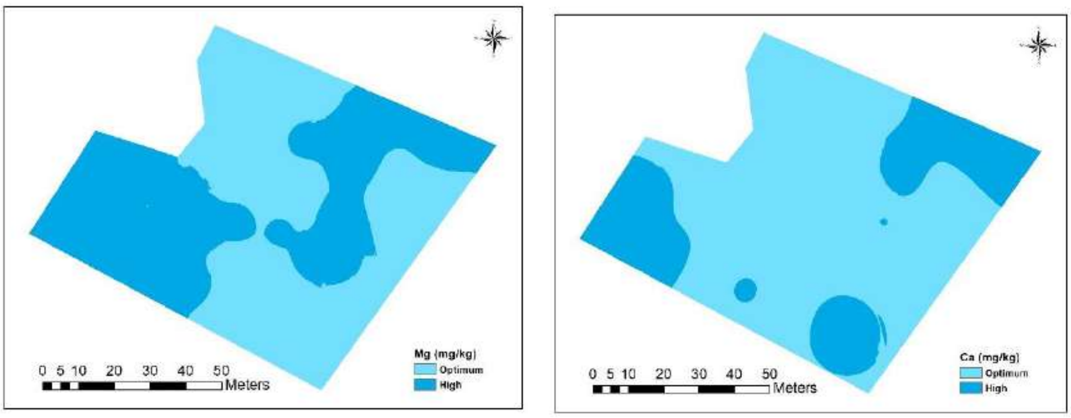

Figure 4. Map of available Ca and Mg

The available K content in the soils of study site were between 0.59 and 19.35 mg kg^{-1} with the mean of 4.18 mg kg^{-1}. The available potassium values were found to be adequate and high. The soil map of available K shows that the study area was sufficient level (Figure 3).

The available Ca content in the soils were between 1294 and 4944 mg kg^{-1} with the mean of 3258 mg kg^{-1}. The map shows that available Ca in the soils were found to be adequate and high. (Fig. 4). In addition to, soil map shows that available Ca content in the soils was more present in both west and east.

The available Mg content ranged from 215.7 to 590.1 mg kg^{-1} with the mean of 471.2 mg kg^{-1} in the soil of study site. The map indicated that available magnesium in the soils were adequate.

Conclusion

The pH of soils in the study area were generally slightly acid and all nutrients were adequate with the exception of phosphorus. The spatial distributions maps of the soil phosphorus showed that soil phosphorus content was deficient in the total study area. Thus, phosphorus fertilizer should be added to the fertilizer programme to increase the phosphorus content in the soils.

In addition to, there were differences in the amount of nutrients in the soils of the study site and soil maps were obtained for nutrients showing the parts of the study site that needed application of fertilizers. These maps can be used for site specific management and present information about soil fertility and thus it prevents incorrect fertilization for hazelnut.

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Assessment of composted and non-composted rice straw incorporation on wheat (*Triticum aestivum*) productivity and soil health

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Abstract

Rice straw (RS) is a valuable organic resource for enhancing soil fertility; however, its direct incorporation poses challenges due to high bulk volume, slow decomposition, and potential allelopathic effects. Although numerous studies have examined both raw and composted RS applications, direct comparisons regarding their impact on wheat growth remain limited. This study investigated the effects of five application rates (S0, S1, S2, S3, S4) of composted RS (CR) and non-composted RS (NCR) on wheat growth components, yield, and soil properties. Methods: Wheat was grown in a pot experiment under greenhouse conditions following completely randomized design (CRD). The results revealed that CR significantly improved plant growth parameters including plant height, stem diameter and tiller number, whereas NCR exhibited a suppressive effect. Both fresh and dry biomass were markedly higher in CR treatments than in NCR ($p < 0.001$). Specifically, wheat yield increased by 85% under CR (S1) but decreased by 63% under non-composted RS (S1) relative to the control (S0). Regardless of straw type, RS application significantly enhanced soil pH, EC and organic carbon (SOC) following the treatment ($p < 0.01$). However, N nitrogen (N) and phosphorus (P) contents were significantly higher in composted RS treatments than in non-composted RS. At the S4 level, CR increased N and P by 25% and 49% compared to control, and by 21% and 6% relative to NCR (S4), respectively. Moreover, RS application significantly improved soil potassium (K) and sodium (Na) contents ($p < 0.01$) irrespective of the straw type. Overall, composted RS considerably enhanced wheat's growth parameters, yield and soil nutrient availability, highlighting the promising role of RS composting in boosting crop productivity and improving soil health. The findings underscore composting as an effective strategy for sustainable RS management in wheat cultivation.

Key words: Composting, nutrients availability, rice straw, soil properties, wheat growth, yield.

Introduction

Rice, the second most commonly cultivated cereal crop in the world after wheat generates approximately 45% straw of the total volume (Robinson 2006). Every year a large amount of rice residue is being produced in the

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rice growing countries leaving an enormous potential of returning these residues back in the soil for next cropping systems. Nevertheless, due to the management difficulties of huge amount of straw, many farmers prefer to burn them on site to dimmish unnecessary efforts (Jin et al. 2020; Singh et al. 2021).When burnt, the residues generate CO2, contaminate the air and resulted in SOM depletion (Mandal et al. 2004). Thus, return of rice straw (RS) back to the field instead of burning has been recommended as an efficient management practice of improving the ability of farmlands to sequester soil organic carbon (SOC) (Liu et al., 2014; Pan GenXing et al., 2004; Xu et al., 2011) and enhancing soil productivity (Singh et al., 2007).

RS is a rich source of K (0.9-1.6%), N (0.5-0.8%), P (0.08%), Ca (0.40%) and Mg (0.24%) (Fu et al., 2021; Sarkar et al., 2017; Shinde et al., 2022), hence can serve as an excellent source for plant available nutrients. Direct incorporation, however requires several tillage operations due to large straw volume, which raise the cultivation costs and perhaps delaying the sowing of next crops with limited window period (Warnock et al. 2010; Yadvinder-Singh et al. 2010). Fresh RS application also poses other challenges, such as the production of phytotoxic compounds e.g., phelolic acids that inhibit plant growth and development (Inderjit et al., 2004; Tsutsuki and Ponnamperuma, 1987). For instance Yang et al. (2016) documented a negative impact of traditional straw return method on seed germination and early growth of cultivated crops. Although, continuous application of RS has been found to affect soil fertility and N content (Ponnamperuma 1984), a number of contradictory findings revealed that retention of RS did not improve crop yield instead exhibited a suppressing impact on crop growth (Chou and Lin, 1976; Liao Ping et al., 2018; Pramanik et al., 2001). Furthermore, during the decomposition process, freshly incorporated straw facilitates CH4 emissions (Huang et al. 2006; Zhang XiaoYan et al. 2012), which contributes to the emerging global warming crisis (Houghton et al. 2001).

Rice is typically a silicon-rich crop, with significant variations in silicon content throughout the plant parts (Dai et al. 2005; Takahashi 1995). This crop has a silica content range between 77 to 82% (Ranasingle 1993). The primary components of RS are cellulose (38.3%), hemicellulose (31.6%), and ash (18.3%) (Pan et al., 2017; Wu et al., 2014). Additionally, RS is rich in lignin (18.5%) and possess a C:N ratio of 80:1 (Kumar et al., 2008; Sharma and Arora, 2011). A multitude of studies elucidated that this high silica, lignin and C:N ratio complicates the microbial decomposition of RS (Pan et al., 2010; Wu et al., 2014) and requires a substantial amount of N during the process (Chu et al., 2007; Li et al., 2019), which in turn, resulting in N deficiency for plants (Jin et al. 2020; Said-Pullicino et al. 2014). Besides, the low decomposition efficiency of RS leads to slower improvement of soil fertility in the later phases of decomposition. All these difficulties implies to explore more practical options for returning rice residues to arable lands (Lian et al. 2012).

Ex situ incorporation of RS such as composting may provide an alternative methods of reducing CH4 emissions, boosting crop productivity and SOC accumulation (Liu et al., 2014; Adachi et al., 1997). Composting can be a promising solution to transform an abundance of RS into organic fertilizer. Several research have emphasized the potential for compost made from crop residues in increasing plant productivity compared to the output of conventional organic systems (Bruchem et al. 1999; Shitani et al. 2000). Nonetheless, comparative studies of composted and non-composted RS are limited, particularly regarding its response to wheat crop performance and post-harvest soil properties. Therefore, this study seeks to address these challenges by composting RS before incorporating into soil, aiming to improve its decomposition efficiency and enhance its benefits to soil and plants. Specifically, the objectives of this research were to investigate (i) the effect of composted and non-composted RS applications on wheat growth attributes (ii) the impacts of different RS treatments on soil pH, EC and SOC (ii) the effectiveness of composted RS as a sustainable solution to enhance nutrients availability in soil.

Material and Methods

Experimental Soil

The soil used in this experiment was collected from the surface layer (0–20 cm depth) of an agricultural field located in Agricultural Faculty's experimental field, Samsun (41° 21' 49.9" N, 36° 11' 19.7" E). The soil was air-dried, ground, sieved through a <4 mm mesh to ensure uniform particle size and homogeneity. No sterilization was performed in order to preserve the native microbial community present in the soil. The basic physicochemical properties of the soil were determined prior to the experiment (Table 2.1).

Organic Material Description

Two types of organic materials were used in the experiment: raw rice straw (NCR) and composted rice straw (CR). Both materials were obtained from the Composting Unit of the Department of Soil Science and Plant Nutrition, Ondokuz Mayıs University. The composted rice straw (CR) was prepared exclusively from RS without the addition of any other organic substrates. The composting process involved microbial inoculation using a locally adapted microbial consortium to facilitate aerobic decomposition. The compost was matured under controlled conditions until it reached a stable and humified form, characterized by a dark color, earthy smell, and crumbly texture. These organic amendments were applied to the soil as per the treatment plan to assess their impact on soil properties and plant performance. The properties of the organic materials used in the experiment (RS and RS compost) are presented in Table 2.2.

Table 1. Preliminary soil properties prior to the pot experiment

Soil properties	Results	Methods
Textural class	Clay	Bouyucus hydrometer method
Sand (2-0.05mm), %	28.69	
Silt (0.05-0.002mm), %	24.33	
Clay (< 0.002mm), %	46.96	
pH	7.18	Soil-water suspension (1:1) method
Electrical conductivity (EC), dSm^{-1}	0.91	
Soil organic matter (SOC), %	1.44	Walkley-Black wet oxidation method
Total N, %	0.26	Kjeldahl method
Available P, mg kg^{-1}	46.98	0.5N NaHCO3 extraction method (Olsen)
Exchangeable K, Cmol kg^{-1}	1.90	Flame Photometer method
Exchangeable Na, Cmol kg^{-1}	0.71	
Exchangeable Ca, Cmol kg^{-1}	29.40	EDTA method
Exchangeable Mg, Cmol kg^{-1}	24.0	
$CaCO_3$, %	0.97	Scheibler calcimeter method

Table 2. Properties of used organic materials

Properties	RS compost	RS	Methods
pH	8.45	8.00	1: 5 RS-water suspension method
EC (dSm^{-1})	4.19	3.29	
N (%)	1.43	1.50	Kjeldahl method
C (%)	36.23	41.26	Weight loss-on-ignition principle
C: N ratio	1:25	1:27.5	
P (%)	0.39	0.31	Vanabdomolybdate yellow method
K (%)	1.32	1.17	Flame photometric method

Experimental Setup

A greenhouse pot experiment was conducted at the Department of Soil Science and Plant Nutrition, Ondokuz Mayıs University, to evaluate the effects of composted and non-composted rice straw (RS) on wheat (Triticum aestivum L.) growth. The experiment was initiated in late November 2024 and lasted for 150 days, concluding in April 2025. Five different application rates of both composted rice straw (CR) and non-composted rice straw (NCR)—0%, 1%, 2%, 3%, and 4% (w/w)—were tested. Each treatment was replicated three times, resulting in a total of 30 pots. Each pot (22 cm diameter) was filled with 3.5 kg of air-dried, <4 mm sieved soil. The pots were arranged in a completely randomized design (CRD).

Treatment and Fertilizer Applications

The composted and non-composted RS materials used in the experiment were supplied by the Composting Unit of the Department of Soil Science and Plant Nutrition, Ondokuz Mayıs University. Prior to application, both types of RS were ground to uniform particle sizes. The RS materials were thoroughly mixed with soil in the respective pots according to the treatment levels described. During plant growth, visible nitrogen deficiency symptoms (notably chlorosis) appeared earlier in the non-composted treatments. To address this, foliar applications of urea (as a nitrogen source) were applied in two equal splits: the first at 30 days after sowing, and the second at 45 days after sowing.

Intercultural Operations

Basically, the intercultural operations were performed for assuring and maintaining the usual growth of the plant. After two weeks of sowing thinning was done for all the pots and 17 seedlings were kept in pot for the final study. Wheat was grown over 4.5 months (November to April 2025). During the growing phase, soil moisture was maintained at field capacity by irrigating every three days to replenish the soil water loss. The plants were infested with some weeds, which were controlled by uprooting them from the pots. Harvesting was done when the plants reached their maturity stage (25^{th} April 2025). Crops from each of the pots were cut separately and taken to be threshed. The cut crops were then threshed, cleaned and packed separately for further processes.

Morphological Data Collection and Recording

Wheat growth attributes such as plant height, tiller number, and stem diameter were recorded from each of the replicated plots. Five plants, with average growth and development, were chosen randomly from each plot for recording the morphological and yield data used in this investigation. The height of the plant was measured from the base of the plant to the tip of the tallest panicle by using a meter scale. Similarly, for every pot tiller number and stem diameter were counted for five random plants and after that the mean value was calculated. Upon the completion of harvesting the grain weight data was recorded and the plant fresh weight data was taken for each pot's plants. Afterwards, the plant samples were dried at oven (65°C for 24 h) to collect the dry matter weights following Eq.1.

$$\text{Dry matter content (g)} = \frac{\text{Dry mass (g)}}{\text{Fresh mass (g)}} \times 100 \qquad \textit{Eq.1}$$

Plant Chlorophyll Analyses

During the flowering stage, leaf chlorophyll content was determined. For this, a fresh leaf sample weighing 0.2 g was collected from each pot and were prepared for pigment extraction following the method of Witham et al., (1971). Shortly, the leaf sample was placed in a mortar and mixed with magnesium oxide (MgO) and sand to aid in cell wall disruption and pigment release. Afterwards, the mixture was diluted using acetone solution (acetone ≥ 99.5%) and placed for centrifugation at 4000 rpm for 5 minutes. Lastly the pigment quantification for three types of chlorophyll (a and b) was carried out using a UV-Vis spectrophotometer, with measuring absorbance values at specific wavelengths corresponding to the respective chlorophyll and the total content was calculated.

Soil Sample Collection and Analyses

For post harvesting soil samples collection, the soil from each pot was collected in two batches. The first batch of soil was collected right way after harvesting and was carefully wrapped in a plastic bag. These soil samples were stored in a refrigerator and labeled for biological properties analyses. On the other hand, for second batch collection, soil from the pot was poured on a separate polythene sheet, air dried and then the larger particles were broken and passed through 2mm sieves for physicochemical properties analysis. This process was followed for all the experimental pots.

Soil Physio-chemical Properties Analyses

The pH and EC of the soil sample was determined using a 1:1 soil-water suspension method, as described by Rowell (2014). Lime content in the initial soil sample was measured by using Scheibler calcimeter method (Martin and Reeve, 1955). Particle size analysis of the soil sample was carried out by hydrometer method (Bouyoucos 1962) and the textural classes were determined by Marshall's Triangular co-ordinate system. SOC was estimated by following the Chromic acid wet oxidation method described by Walkley and Black (1934). In short, 1 g air-dried soil samples were treated with and 1 N potassium dichromate (K_2CrO_7) and sulfuric acid (H_2SO_4). The remaining unused chromic acid was titrated with ferrous sulfate ($FeSO_4.7H_2O$) solution, and the SOC content was determined. The total soil N content was analyzed by using Kjeldahl method (Jackson 1973). Available soil P was extracted from the soil with 0.5 M sodium bicarbonate ($NaHCO_3$) at pH 7.5 (Jackson, 1973), and the content was determined by using spectrometer by following the methods of FAO, (2021). For exchangeable cations determination, the soil was extracted with 25ml 1 N ammonimun acetate ($NaAO_C$) solution (pH = 8) and the exchangeable K^+ and Na^+ contents were measured by an Atomic Absorption of Photometer of Flame Photometer method (Page et al. 1982). Exchangeable Ca^{2+} and Mg^{2+} concentration were estimated by EDTA methods as suggested by Barrows and Simpson, (1962).

Statistical Analysis

The statistical analyses for this study were performed by using Origin pro and R-studio. Two-way analysis of variance (ANOVA) were used to explore the effects of composted and non-composted rice straw and their different rates on wheat growth and yield attributes, plant available soil nutrients (N, P, K, S), SOC, and biological properties. The differences between means were analyzed using the Tukey's LSD-test at 0.05 level. Significant applications were denoted with * at 0.05, ** at 0.01 and *** at <0.001.

Results and Discussion

Effects on Wheat Growth Attribute

The study showed that the application of various rates of composted and non-composted RS had significantly affected plant height data ($p < 0.01$) (Fig 3.1a). Besides, the interaction effect of treatment and rate was also significant. Plant treated with CR showed an increasing trend with high application rates (S1-S3), while plant under NCR treatment exhibited an opposite trend with increasing rate. Overall, under CR, S2 demonstrated a better plant height than all rates and resulted in 19% and 40% more height than S0 and their counterpart RS (NCR-S2). Additionally the impact of various application rates of composted and non-composted RS on wheat leaves chlorophyll content depicted a significant effect (Fig 3.1b), however the interaction effect of treatment and application rates remained insignificant. CR-S4 exhibited the highest chlorophyll production (1.57 mg g^{-1} FW) which is 1.46- fold higher than CR-S0 and 1.63-fold more than its counterpart RS rate (NCR-S4).

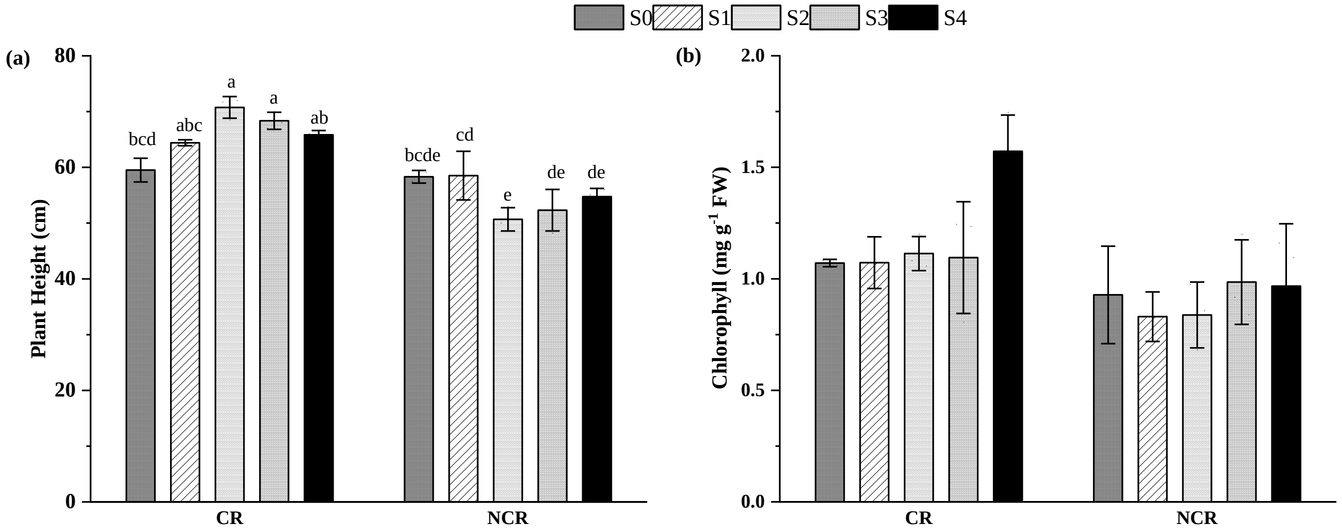

Figure 1. Effect of composted and non-composted RS on (a) plant height and (b) total cholorophyll content

The effect of RS on wheat tiller has been presented in Figure 3.2a. Results revealed that the types (CR and NCR) and rate of RS (S0, S1, S2, S3 and S4) had a significant impact on the tiller number ($p < 0.001$ and $p < 0.01$, respectively). The interaction impact of types and different rates of rice straw also had a significant effect on tiller number ($p < 0.01$).

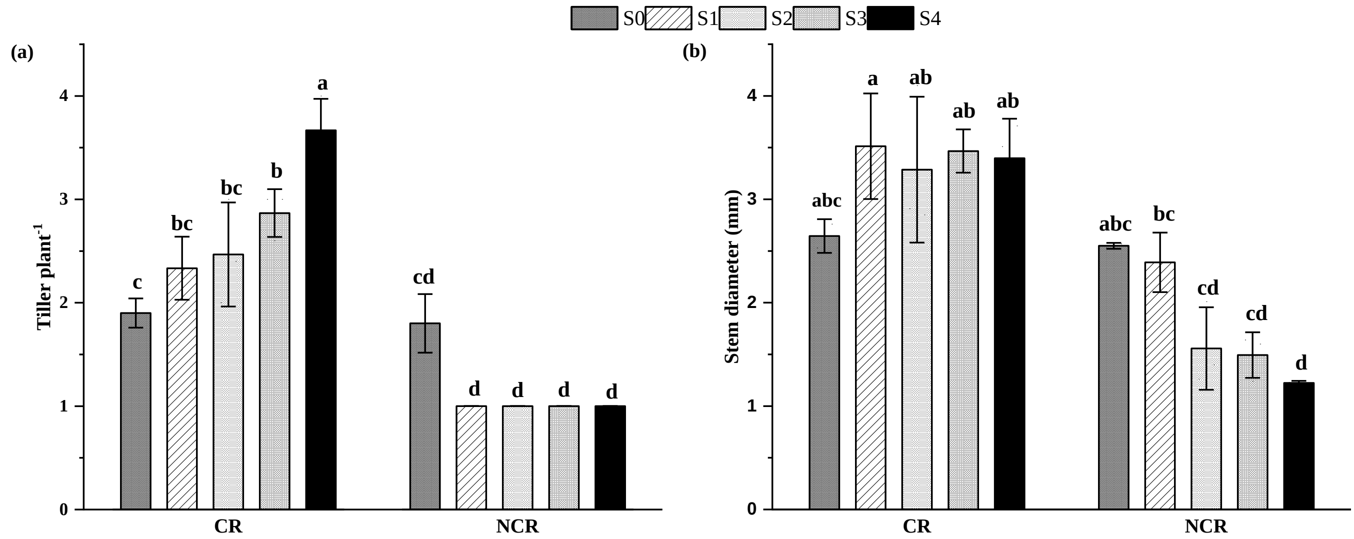

Figure 2. Effect of composted and non-composted RS on (a) Tiller number and (b) Stem diameter

Among the treatment-rate combination, CR-S4 demonstrated maximum tiller count (3.66) followed by CR-S3 (2.86), while with NCR application, all the rates exhibited similar number (1) except S0. CR (S4) displayed 266% and 83% more tiller plant^{-1} than the NCR and S0. Besides, we found a significant correlation between tiller number and soil N (r =0.71) and P (r =0.55) availability (Fig 3.5). The types of RS (CR and NCR) also displayed a significant effect ($p < 0.001$) on wheat stem diameter while the effect of different rates (S1, S2, S3 and S4) of RS were insignificant (Fig 3.2b). It appeared that CR performed better in producing higher stem diameter than the NCR. Among the treatment, S1 in CR showed maximum stem diameter of 3.51 mm, which is statistically identical to S0, S2, S3 and S4 of same RS type. Contradictory, S4 in NCR, resulted in a minimum stem diameter of 1.22mm, which is statistically lower than the S0 of same RS type.

Effects on Plant Weight and Yield

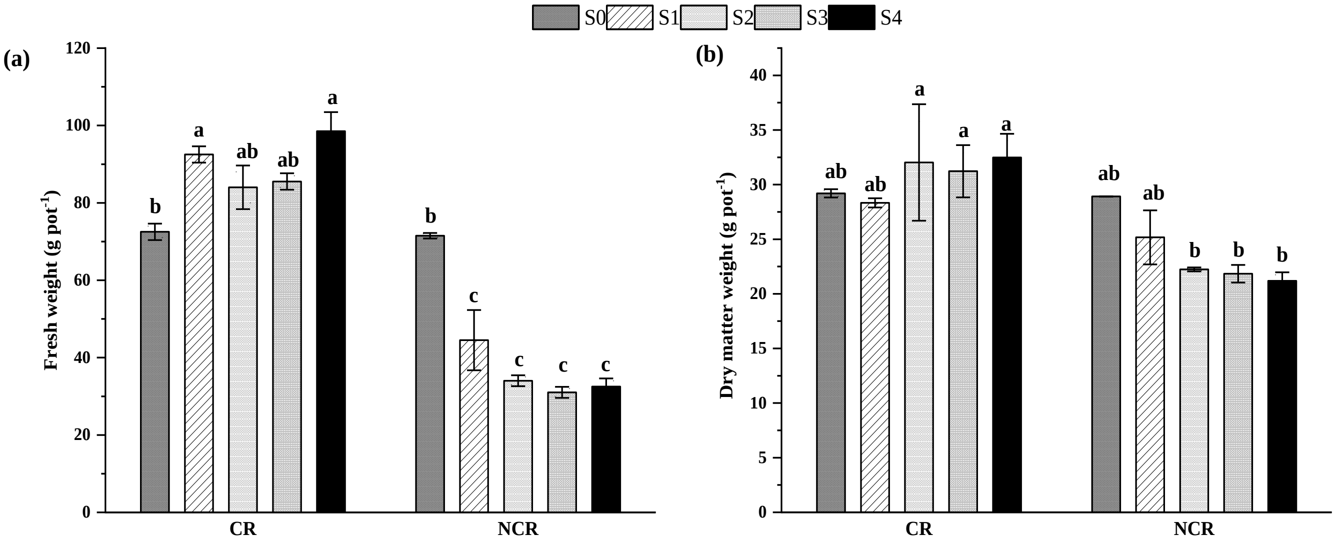

Figure 3. Effect of composted and non-composted RS on (a) plant fresh weight and (b) dry matter weight

The study showed a highly significant effects of RS treatment and application rate on plant fresh biomass weight with post hoc comparisons (Tukey's HSD, $\alpha = 0.05$) showed distinct groupings among the treatments and rates (Fig 3.3 a). Besides, the significant interaction effect of treatment and rate ($p < 0.001$) implies that the effect of composted vs. non-composted RS depended on the application rate. Composted RS significantly enhanced plant fresh weight compared to non-composted RS, particularly at higher application rates (S1–S4). The highest mean weight (98.5) was obtained under CR-S4, which was statistically identical to CR-S1 (92.5) but was markedly higher than all NCR rates. On the other hand, under NCR, various rates of RS (S1-S4) surprisingly found to result in less plant weight in comparison to NCR-S0.

Regarding dry matter weight, treatment and interaction demonstrated a significant influence on the weight data while the effect of different rates remained unchanged (Fig 3.3 b). Likewise fresh biomas, increasing application doses of composted RS significantly improved plant dry matter weight with CR-S4 exhibiting highest value of 32.48 g pot^{-1}. However, under NCR application, all the rates produced lower mean dry matter weight compared to control (NCR-S0). Moreover, CR produced significantly higher grain weight ($p < 0.001$) than NCR across all rates (Fig 3.4). Within CR, S1 demonstrated the highest weight (13.22 gm) followed by S3 (12.07g), S2 (10.82g) and S4 (9.53g), while NCR rates (S1–S4) were statistically inferior to S0, with S4 (0.66g) being the least effective among all treatment-rate combination. İnterestingly an extenuating trend in grain weight with higher application rates (S1-S4) was observed under both RS treatemnt except CR-S3. Overall, CR-S1 resulted in 85% more grain yeild than CR-S0 while, a reduction in grain weight by 63% was noticed in NCR (S1) compared to control (NCR-S0). Furthermore, the grain weight was significantly contributed by tiller number ($r = 0.83$), steam diameter ($r = 0.97$) followed by fresh biomass weight ($r = 0.94$) and dry matter yield ($r = 0.87$) (Fig 3.5).

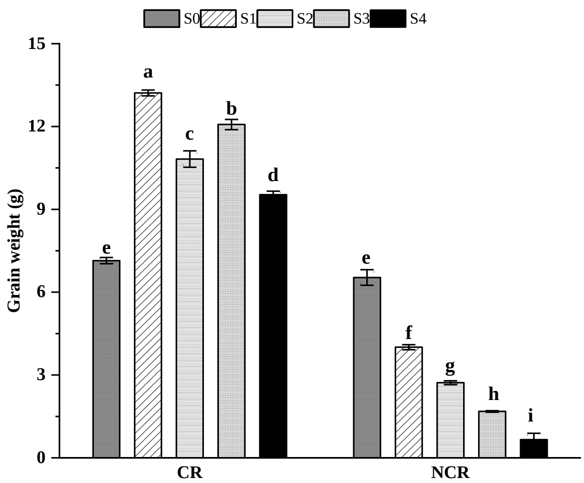

Figure 4. Effect of composted and non-composted RS on wheat grain yield

Effect on Post-Harvesting Soil pH, EC and SOC

The experiment displayed a significant impact of RS type and application rate on soil pH and EC (Table 3.1). On the other hand, the impact of interaction effect of various rates and RS types on these measured parameters was found to be insignificant ($p > 0.05$). Analyses revealed that different application rates resulted in higher pH value compared to control (S0) in both RS treatment with S1 under CR exhibiting maximum mean of 7.6 followed by S3 (CR) and S1 (NCR), and NCR-S0 showed the minimum pH value of 7.32. Interesting under both straw treatments, S1 displayed higher pH whereas remaining higher application rates (S2-S4) showed a declining trend with an increasing rate. As for EC, the rate S1 in both rice straw treatments resulted in higher EC followed by S4, where composted RS demonstrates statistically higher EC than non-composted RS. Overall, composted RS (S1) showed the maximum EC (1.08 dSm^{-1}) which is statistically identical to S2, S3 and S4 of similar straw type and S1 of non-composted straw type. The S0 on the contradictory demonstrated minimum EC in both straw types.

Table 1. Effect of composted and non-composted RS on post harvesting soil pH, EC and SOC

Treatment	Rate	pH	EC (dSm^{-1})	SOC (%)
CR	S0	7.35±0.04	0.72±0.04	2.13±0.00
	S1	7.60±0.05	1.08±0.08	2.45±0.09
	S2	7.54±0.25	0.88±0.04	2.53±0.11
	S3	7.57±0.30	0.93±0.12	2.62±0.16
	S4	7.47±0.25	1.04±0.09	2.78±0.16
NCR	S0	7.33±0.21	0.71±0.01	2.12±0.00
	S1	7.56±0.26	0.90±0.09	2.47±0.20
	S2	7.50±0.01	0.79±0.00	2.75±0.19
	S3	7.52±0.01	0.73±0.00	2.83±0.47
	S4	7.45±0.04	0.87±0.01	2.90±0.29
LSD (0.05)				
Treatment		*	***	ns
Rate		***	***	**
Treatment x Rate		ns	ns	ns

Note: The common letter (s) within each column indicate non-significant differences based on the tukey's lsd test at 0.05. *; significantly different at 0.05 level, **; significantly different at 0.01 level, and ***; significantly different at < 0.001 level, ns; not significantly different

Besides the study showed that three was no significant differences in SOC levels with the treatments, however, the different application rates (S0-S4) displayed a significant impact with rates S1–S4 (both treatments) generally outperformed S0. Among the rates, S4 in NCR exhibited the highest SOC content (2.90%) followed by NCR-S3 (2.83) and the lowest content (2.13%) was recorded in S0 under CR treatment. The non-significant interaction effect ($p > 0.05$) indicated that the impact of rates was consistent across both composted and non-composted treatments.

Soil Nutrients Availability

The changes in the post-harvesting soil macro-nutrients and Na availability under composted and non-composted RS treatment and application rate are presented in Table 3.2. The effect of RS type and application rate was noticed to have a significant impact on soil total N content ($p < 0.01$). Besides the interaction effect of RS type and rate also found to be significant with treatment-rate CR-S4 resulted in highest N content (0.26%) among all the combinations and resulted in 25% and 21% more N than S0 (CR) and its counter straw type (S4 in NCR), respectively while on the contrast, NCR-S0 exhibit the lowest N level (0.209%). In terms of P content, both straw types and application rate showed a significant impact (Table 3.2). Treatment CR resulted in more soil available P than NCR however, no distinct pattern was observed in the P level with increasing RS rate. In both treatments the lowest value was found in S0. Additionally, the interaction effect of treatment and rate also demonstrated a significant influence on post-harvesting soil available P level with CR-S2 and NCR-S4 resulted in 61% and 41% more P over S0 under respective straw types.

The various application rates of RS demonstrated a significant impact on soil K content whereas, the effect was insignificant in terms of treatment and treatment-rate interactions. The rate S4 exhibited the highest soil available K content and showed 2.2 times more soil available K than S0 under both CR and NCR treatment.

Table 2. Mean interaction effect of RS types and rates on post-harvesting soil nutrients content

Treatment	Rate	N %	P (ppm)	K cmol (+)/ kg	Na cmol (+)/ kg	Ca cmol (+)/ kg	Mg cmol (+)/ kg
CR	S0	0.21±0.0^{c}	61.69±2.09^{c}	0.99±0.02	0.65±0.03	24.60±0.33	19.48±0.21
	S1	0.22±0.0^{bc}	78.62±4.79^{bc}	1.70±0.11	1.72±0.47	25.32±0.31	19.87±0.47
	S2	0.22±0.0^{abc}	99.45±4.22^{a}	1.50±0.16	1.03±0.18	30.67±4.88	16.02±3.32
	S3	0.25±0.01^{ab}	93.0±5.74^{ab}	1.77±0.23	1.63±0.73	25.28±2.88	17.00±4.24
	S4	0.26±0.03^{a}	92.06±6.27^{ab}	2.18±0.02	1.43±0.12	27.12±0.78	17.37±3.87
NCR	S0	0.20±0.0^{c}	61.28±1.9^{c}	0.97±0.03	0.62±0.01	24.43±0.05	19.38±0.31
	S1	0.21±0.02^{c}	62.36±0.01^{c}	1.79±0.33	0.95±0.11	27.83±4.48	27.25±2.52
	S2	0.23±0.01^{abc}	74.86±1.33^{bc}	1.62±0.14	0.75±0.07	26.32±3.13	20.82±3.51
	S3	0.22±0.03^{abc}	74.87±0.57^{bc}	1.96±0.10	1.20±0.27	25.87±2.50	20.03±1.65
	S4	0.21±0.01^{bc}	86.82±2.66^{ab}	2.14±0.09	0.88±0.07	25.95±0.54	20.43±1.13
Treatment *F-value*		11.63**	33.99***	0.95^{ns}	9.46*	0.33^{ns}	9.86*
Rate *F-value*		6.79**	23.50**	31.37***	4.64*	2.12^{ns}	2.78^{ns}
Treatment X Rate *F-value*		4.48*	3.97*	0.37^{ns}	0.84^{ns}	1.57^{ns}	1.12^{ns}

Note: In each column, the means values denoted by the same letter are not significantly different at LSD 0.05 level, *; significantly different at 0.05 level, **; significantly different at 0.01 level, and ***; significantly different at < 0.001 level, ns; not significantly different.

Regarding the soil available Ca content, though there was a slight increase in soil Ca with higher application rate compared to control (S0) in both treatments, statistically the effect was not insignificant ($p > 0.05$). By contrast, the treatment had a significant impact on soil available Mg content with non-composted RS resulted in higher Mg content than composted RS, while rate and treatment-rate interaction did not show any significant effect on the measured attribute. Lastly, for soil available Na content, the straw treatment and application doses displayed a significant effect ($p < 0.05$) with composted RS resulting in higher Na content than non-composted RS. In CR, the maximum Na content was observed under S1 while in NCR, S3 presented the highest Na value. Under both straw types, the minimum Na content was found in S0 (control).

	PH	*TChl*	*TN*	*SD*	*FW*	*DW*	*GW*	*pH*	*EC*	*SOC*	*N*	*P*	*K*	*Na*	*Ca*	*Mg*
PH	1.00															
TChl	0.59	1.00														
TN	0.84	0.87	1.00													
SD	0.92	0.59	0.87	1.00												
FW	0.88	0.70	0.93	0.96	1.00											
DW	0.90	0.66	0.90	0.93	0.95	1.00										
GW	0.89	0.52	0.83	0.97	0.94	0.87	1.00									
pH	0.30	-0.01	0.08	0.24	0.05	-0.04	0.29	1.00								
EC	0.59	0.55	0.60	0.60	0.56	0.39	0.60	0.64	1.00							
SOC	-0.21	0.18	-0.09	-0.39	-0.39	-0.44	-0.35	0.49	0.30	1.00						
N	0.41	0.73	0.71	0.41	0.43	0.42	0.39	0.31	0.52	0.51	1.00					
P	0.61	0.54	0.55	0.36	0.38	0.36	0.42	0.49	0.55	0.57	0.64	1.00				
K	-0.03	0.33	0.07	-0.16	-0.19	-0.28	-0.18	0.59	0.57	0.91	0.53	0.53	1.00			
Na	0.55	0.50	0.58	0.58	0.51	0.35	0.63	0.73	0.80	0.35	0.63	0.56	0.55	1.00		
Ca	0.40	0.15	0.13	0.17	0.07	0.20	0.11	0.45	0.26	0.28	0.12	0.55	0.27	0.04	1.00	
Mg	-0.54	-0.60	-0.68	-0.44	-0.58	-0.57	-0.53	0.11	-0.11	-0.07	-0.53	-0.67	0.07	-0.29	-0.06	1.00

-1, -0.8, -0.6, -0.4, -0.2, 0, 0.2, 0.4, 0.6, 0.8, 1

Figure 5. Pearson correlation matrix among wheat growth and yield parameters and associated soil nutrient contents. The gray, red, and white color correspond positive, negative, and neutral correlation, respectively. Here: PH, plant height; TN, number of tillers; SD, stem diameter; TChl, total chlorophyll; FW, fresh biomass weight; DW, dry matter weight; GW, grain weight; SOC, soil organic carbon

Discussion

Wheat Growth and Productivity

In our current study, composted RS demonstrated an improved growth parameter e.g., plant height, tiller number, stem diameter and chlorophyll contents which might resulted in higher biomass and grain production under CR treatment. NCR, on the contrary, suppressed the growth and productivity of wheat. RS typically takes 2.5 months to achieve 61% decomposition percentage under field condition (Yadvinder-Singh et al. 2004). Therefore, the reduction in plant height in this study for NCR (Fig 3.1a) suggests potential negative effects of RS during the decomposition process e.g., nutrients immobilization (Asaduzzaman and Pramanik, 2005; Fog, 1988; Jin et al., 2020). Generally, straw requires a lot of N during its microbial decomposition process (Chu et al. 2007), thus the microbial activities take up the soil's available N and compete with wheat growth for it (Kumar and Goh, 2003). Consequently the high C:N ratio of RS denitrifies during the decomposition process causing the seedlings to grow slowly and exhibit yellow appearance (Yan et al., 2011). Apart from causing N immobilization, RS has long been reported to exudate phytotoxic compounds such as phenolic acids that known to suppress plant growth through affecting mineral nutrients acquisition, photosynthesis, chlorophyll production, and dry matter weight (Chou and Lin, 1976; Inderjit et al., 1994; Thompson, 1985). This might be attributed to the lower tiller production and steam diameter under NCR treatment. Some past investigation also documented a reduction in wheat tiller (Jin et al. 2020; Witt et al. 2000) and rice tillering capacity Tian et al., (2022) with non-composted wheat straw application which is in line with our result. This advantage can be resulted from the enhanced availability of nutrients such as N, P, and K with CR application, which are essential for plant growth and development (Yadvinder-Singh et al., 2004; Suriyagoda et al., 2014). Overall, in our current study, the incorporation of CR (S4) displayed 266% and 83% more tiller plant^{-1} than the NCR and S0, highlighting the potential benefits of higher rates of CR application in improving plant's vegetative growth.

Chlorophyll, the most abundant leaf pigment, is an important indicator for plant growth and nutrient status estimation due to its crucial role in photosynthesis. According to Suhani et al., (2024) incorporation of organic amendments can facilitates total chlorophyll production which is in consistent with our results regarding the improved plant chlorophyll levels with higher doses of composted RS. In another study of Sarangi et al., (2021) also mentioned a vigorous seedling growth and chlorophyll a and chlorophyll b content in rice leaves with decomposed RS addition. The low chlorophyll levels in this experiment under NCR treatment might be related to the inhibitory impact of the toxic chemicals on plant photosynthesis that exuded during the microbial degradation of RS (Asaduzzaman and Pramanik, 2005; Pramanik et al., 2001). We deduced that the reduced fresh and dry plant weight in NCR with higher RS rates is the result of N immobilization during the early vegetative growth phase of wheat. In their investigation Mahdizadeh et al., (2025); Tian et al., (2022) recorded a reduction in plant fresh biomass and dry matter with undecomposed straw incorporation which is in consent with our current findings. Similar findings on composted RS on fresh and dry biomass was reported by a number of previous studies (Ali et al., 2006; Sarangi et al., 2021; Y. Zhang et al., 2024) that also aligns with our result.

Soil pH, EC and SOC

According to our results, both composted and non-composted RS incorporation resulted in an increase in soil pH and EC compared to control (S0). The plausible reasons for higher pH with RS application might be resulted from microbial NH_4^+ immobilization (Ali and Nabi, 2016; Said-Pullicino et al., 2014) that may cause a reduction in H^+ ion release from nitrification and eventually lead to a slight raise in soil pH. Additionally, RS contains cations like K^+, Ca^{2+}, and Mg^{2+} (Li et al., 2014; Saito et al., 1994), which could displace H^+ from soil colloids, therefore resulted an increment in the soil pH post RS treatment. RS also release a range of organic acids during the decomposition (Kumari et al. 2008) which might be reason behind the declining pH level with higher application rates (S2-S4) in this experiment. Identical findings was also mentioned by Saothongnoi et al., (2014) who recorded a raise in soil pH post RS incorporation. However, Cao et al., (2022) documented that rotary tillage combined with straw covering under no-till conditions reduced soil pH from 7.7 to 7.2, implying the variability of outcomes depending on soil types and residue composition. Apart from that our results regarding a rise in soil EC with composted and non- composted RS application supports by Saothongnoi et al., (2014) who also reported a raise in soil EC with incorporation. However, in another investigation, Mahmoud et al., (2009) reported a slight drop in soil EC that contradicted with our results. The possible reason for the increasing EC with RS application might result from the presence of minerals in RS and RS-compost. Similar results and explanation was stated by Cheng et al., (2017) who reported an insignificant impact of RS and composted RS on pH and a raise in soil EC with both conventional and higher rates (10 and 30 Mg ha^{-1}) under a paddy field study conducted in northeastern Japan. However, some studies reported a reduction EC with straw compost application (Kim et al., 2017; Li et al., 2023). The role of RS in minimizing high EC might attributed to its contribution to its long-term effect on aggregate formation (Sodhi, Beri, and Benbi 2009), improvement of total soil porosity and water content (Barus et al., 2023) which might be less pronounced in our short-term study.

In agricultural soils, C accumulation or sequestration typically associated with soil productivity and quality, hence a decline in SOC could adversely impact crop yield. Multiple studies have already conceded the effect of various straw incorporation as an organic amendments in increasing SOC level (Liu et al., 2021; Mahmoud et al., 2009; Sodhi et al., 2009; Barus et al., 2023). In this present study, all amended rates (S1–S4) produced significantly higher SOC than the control (S0), regardless of straw type. Though S4 under NCR yielded the highest mean, it did not differ statistically from other amended rates (S1–S3), implying a diminishing return at higher application rates. Our findings support by Watanabe et al., (2009) who found no significant differences in the SOC with the types of applied RS compost. In an earlier investigation, Liu et al., (2021) reported that adding RS significantly raises the amount of SOC by 18.5% compared to control also support our current result. Consequently, depending on our results both composted and non-composted RS could be a reliable source for improving SOC stock.

Soil Nutrient Availability

In our study, higher application rates of both composted and non-composted RS improved soil total N content P, K, Ca and Mg availability over S0 (control). The improved nutrients content primarily resulted from the and release and mineralization of corresponding nutrients from the applied straw (Cheng et al. 2017). The high C: N of non-composted RS demands high available N during the microbial decomposition process which causes N immobilization (Yadvinder-Singh et al. 2010) and ultimately enhanced total soil N content in this experiment. The composted RS on the contrary possessed a low C: N reflecting a quick release of soil nutrients than the undecomposed RS which might be the probable reason for higher N and P levels in CR treatment over NCR. Consequently, composting reduces the total C content of the organic materials during the bioprocess and facilitates the accumulation of essential nutrients like P, K, Ca and Mg (Kausar et al., 2014; Suhani et al., 2024). Similar findings and explanation was also explained by van Asten et al., (2005) who reported an improved N availability with straw application but not available P content. However, an earlier study of Saothongnoi et al., (2014) documented that incorporation of RS ash improved the soil P content yet the effect was insignificant among the rate. Besides the study also recorded a significant difference in K level with different RS ash treatment (Saothongnoi et al. 2014).

Additionally, straw is can effective source of soil K (Yadvinder-Singh, Bijay-Singh, and Timsina 2005) which is evident in this current study where the higher application rates for both composted and non-composted RS enhanced soil available K content. Crop straw concealed to contains 80% of the crop's total K intake (Yu et al., 2010;), and the K presents in straw has the fastest release due to its high solubility to water (Yadvinder-Singh et al. 2005; Yan et al. 2019). In their investigation Saothongnoi et al., (2014) recorded an increment of 42% K with rice straw application compared to control that supports our findings as well as highlights the potential of RS in soil nutrient management. Asaduzzaman and Pramanik (2005) mentioned an extenuation in soil N, P and K and a slight increment in Ca and Na amount with excess RS application which aligns with our result regarding N content, however the P and K showed an opposite trend while the Ca and Mg observed to be increased with higher RS rates. Our outcomes are also in consent with the findings of (Mahmoud et al. 2009), reporting a raise in Ca and K levels with composted RS introduction. Overall, our findings concerning the enhanced soil available nutrients with added composted RS is supported by a series of past studies (Cheng et al., 2017; Han et al., 2020; Liu et al., 2021). Moreover, application of corn straw compost found to noticeably improve physiochemical properties of saline-alkali soil e.g., reduce soil pH and EC and enhanced N and P availability (Li et al., 2023) suggesting the potential of straw compost in alleviating saline soil health.

Conclusion

This study demonstrated that the incorporation of both rice straw (RS) into soil improved soil health indicators such as SOC, total N, available P, K, Ca and Mg content compared to control (S0). However, CR treatments resulted in significantly higher N and P compared to NCR treatments. Post-harvest analysis revealed increased soil pH and EC with increasing RS application rates, where CR found to be outperformed NCR. In terms of plant performance, the application of CR—particularly at higher doses—enhanced wheat growth parameters including plant height, stem diameter, tiller number, chlorophyll contents, fresh and dry biomass, and grain yield. In contrast, increasing rates of NCR resulted in a marked decline in these attributes, even performing worse than the control. This contrast emphasizes the negative effects of applying undecomposed straw directly, highlighting the importance of composting in unlocking the agronomic potential of RS. Notably, while a low application rate of CR (1%) was sufficient to improve wheat productivity, the highest CR rate (4%) was more effective in enhancing SOC levels and nutrient availability.

In conclusion, this study elucidates that the use of composted rice straw (CR) as an organic amendment is a promising and sustainable approach for improving crop productivity, soil biochemical properties, and overall soil health, while mitigating the detrimental impacts associated with direct RS incorporation.

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Impact of long-term power station emissions on the distribution of priority polycyclic aromatic hydrocarbons in soil

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Abstract

Soils near industrial sites often contain polycyclic aromatic hydrocarbons (PAHs), which are carcinogenic and persistent organic contaminants. To develop a remediation strategy and understand the risks to the environment, it is important to study how PAHs accumulating and degrading over the time. The objectives of this research was to study how the increasing of industrial activity affects the types and amounts of 15 priority PAHs in soils affected by a large power plant in the southern Russia. Methods of research: Over the ten years, soil samples were collected to study the tendencies of 15 important PAHs distribution due to increasing of industrial pollution. Quantitative determination of PAHs in the extracts was carried out by high-performance liquid chromatography (HPLC) using an Agilent 1260 system with a fluorescence detector, in accordance with the international standard ISO 13877-2005. Results: The study found that between 2012 and 2022, the total amount of 15 priority PAHs, as well as the levels of individual PAH compounds, increased significantly in the affected soils. This tendences were particularly noticeable for the more easily degrading low-molecular-weight PAHs compounds, indicating that the soil's biodegradation potential to PAHs was limited by the continuous input of new contaminants. Conclusions: The main source of PAHs accumulation in the topsoil was the strength of the pollution sources combined with the area's typical wind distribution according the prevailing wind direction rose. In addition the main feature of aerotechnogenic pollution in the studied zone was accumulation of the high-molecular-weight compounds like fluoranthene and pyrene, which becomes more prevalent.

Keywords: environmental impact, pollutant accumulation, soil contamination, technogenic load, coal burning, electric power station.

Introduction

After deposition onto the soil surfaces, polycyclic aromatic hydrocarbons (PAHs) undergo two opposing groups of processes: sorption and accumulation, as well as migration, biodegradation, and biotransformation, leading to their dissipation (Lodygin et al., 2021). Consequently, changes in PAHs composition becomes an informative indicator of soil contamination by organic pollutants (Abakumov et al., 2021; Dymov et al., 2018; Gennadiev et al., 2020). Determining the full composition and concentrations of priority PAHs provides the understanding of the degree of ecological impact and is important for environmental risk assessment (Dudnikova et al., 2023b; Lisovitskaya and Mozharova, 2013; Su et al., 2022).

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Numerous studies currently focused on PAHs concentrations in soils within the affected zones of various industrial facilities. Hong et al. (2020) analyzed the total content of 47 PAHs in soils from residential, industrial, and background areas in China, Vietnam, India, South Korea, and Japan. Their results demonstrated that PAHs level in soils affected by industrial factories exceeded background concentrations by more than 20 times compare to the background values. According to Zhang and Chen (2017), the total concentration of 16 priority PAHs in background, residential, and industrial soils in all China was approximately 700 ng/g. In industrial regions of Lebanon, the total concentration of 16 PAHs in soils reached 4000 ng/g, with 4-ring PAHs constituting about 35% and 5-ring PAHs accounting for 20% (Soukarieh et al., 2018). Studies in European countries revealed that forest soils within the impact zone of a power plant predominantly accumulated 4-ring PAHs, with total concentrations of 14 PAHs reaching up to 600 ng/g (Lasota and Błońska, 2018). In the vicinity of a chemical plant in Dąbrowa Górnicza, a major industrial area in Poland, the total concentrations of 16 PAHs reached 4000 ng/g (Koltowski et al., 2016).

A key challenge in modern systems ecology remains the limited understanding of the metabolic and adaptive potential of soil microbial communities. In this context, the present study aimed to investigate the temporal dynamics of priority PAHs in soils near a power plant over a ten-year monitoring period.

Material and Methods

Study Area

The present study focuses on soils located in areas adjacent to the Novocherkassk State District Power Plant. This is one of the largest power plants in southern Russia, with an installed capacity of approximately 19 GW. In 2017, its electricity generation accounted for about 7% (63.5 billion kWh) of the total national output. The power plant ranks second in electricity production across the Russian Federation. During 2017–2018, the station's quarterly electricity generation fluctuated between 13,149 and 17,538 million kWh, with the lowest generation typically observed in the summer months. The power plant has a significant impact on the environmental situation of both the city of Novocherkassk (Kravchenko et al., 2024), where the average concentration of benzo[a]pyrene exceeds the permissible limit by 16.4 times, and the Rostov Region as a whole. In 2017 alone, the total volume of emissions from the enterprise amounted to about 220,000 tons. The main components of emissions are ash, sulfur dioxide, nitrogen oxides, soot, vanadium pentoxide, iron oxide, chromic anhydride, hydrogen fluoride, etc. (Chaplygin et al., 2018).

To assess the PAH content in soils affected by the plant's emissions, 25 monitoring points were established in the adjacent territory (Figure 1), taking into account the prevailing wind directions. When selecting the points, regional wind regimes and soil-geomorphological features of the territory were considered. The monitoring points were conditionally divided into three groups. The first group includes points located in the western and north-western sectors, in the direction of prevailing winds up to 20 km from the power plant (sites No. 4, 5, 8, 9, 10, 13, 18, 19). The second group includes areas located within a 3 km radius from the plant, in the zone of the expected diffusion redistribution of emissions (areas No. 1–3, 6, 7, 11, 12, 16, 17). The third group includes areas to the east and northeast, against the prevailing wind direction, up to 12 km from the facility (areas No. 14, 15, 20–25). The soils of the study area are predominantly represented by Haplic Chernozems characterized by a light, medium and heavy loamy granulometric composition, as well as light clay soils as well as Fluvisols.

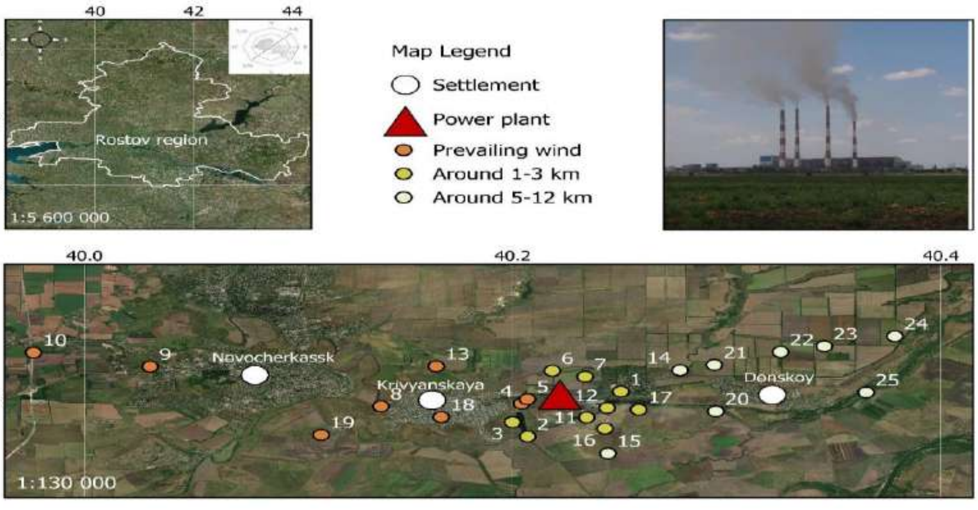

Figure 1. Map-scheme of the monitoring sites

Table 1. Physical and chemical properties of soils at monitoring sites

Statistical parameters	Clay fraction (%)	Silt %	C_{org} (%)	Exchangeable cations Ca^{2+} (cmol(+))	Exchangeable cations Mg^{2+} (cmol(+))	pH
Monitoring year – 2012						
Mean	41.8	20.8	2.0	26.3	3.2	7.5
Median	42.1	17.9	2.1	26.3	3.5	7.6
Minimum	7.5	2.1	0.9	4.6	0.6	6.2
Maximum	68.2	37.0	3.5	39.8	5.1	8.0
Standard deviation	15.5	10.0	0.6	9.3	1.2	0.4
Coefficient of variation	37.1	48.3	31.6	35.4	36.0	5.0
Monitoring year – 2022						
Mean	42.9	20.9	2.0	27.5	3.2	7.4
Median	44.3	17.5	2.0	30.3	3.1	7.4
Minimum	7.0	2.0	0.8	4.0	0.5	6.6
Maximum	67.6	39.2	3.0	39.5	4.9	8.0
Standard deviation	15.4	10.2	0.6	8.9	1.2	0.4
Coefficient of variation	35.9	49.0	30.8	32.5	36.3	5.0

Methods

Soil sampling and analytical methods

Soil samples were collected using the envelope method at a depth of 0–20 cm (GOST 17.4.3.01-2017, 2018).

Determining physical and chemical soil properties

The main physicochemical properties of soil samples were determined: organic carbon content – by bichromate oxidation method with titrimetry; content of granulometric fractions of physical clay (<0.01mm) and silt (<0.001mm) – by sedimentation method using Kachinsky pipette with pyrophosphate preparation (Korchagina and Vadyunina, 1986); pH of soil samples was determined by potentiometric method in the suspension of soil: water 1:2.5.

Identification and quantitative analysis of PAH content in soil samples

To determine the PAHs, 1 g of soil sample was weighed each. To remove the interfering lipid fraction, the soil sample was saponified by boiling for 3 h in 30 ml of 2% potassium hydroxide solution in a water bath with reflux condenser. PAH extraction was carried out with 98% purity n-hexane (ISO 13877-2005, 2020). For this purpose, 15 ml of hexane was poured into the sample and placed on a shaker. After 10 min, the hexane supernatant was carefully poured into a separating funnel. The operation was repeated three times. After that the hexane layers were separated from the residual fraction of the alcoholic alkali solution on the separating funnel. For mechanical purification and removal of residual liquid, the extract was filtered through a paper filter with anhydrous sodium sulphate. The hexane extract was then evaporated at a rotary evaporator. After evaporation the precipitate was dissolved in 1 mL of 99.9% acetonitrile.

Samples were analysed for the presence of PAHs using an Agilent 1260 Infinity high-performance liquid chromatograph (HPLC) (Agilent Technologies, Santa Clara, CA, USA) equipped with fluorescence and UV detectors, in accordance with the requirements of ISO 13877-2005 (ISO 13877-2005, 2005). The HPLC system was equipped with a Hypersil BDS C18 reversed phase column (Agilent Technologies) (125 × 4.6 mm, 5 μm). A mixture of 99.9% acetonitrile (Cryochrome, Moscow, Russia) (75%): bidistilled water (25%) at a flow rate of 0.5 ml min-1 was used as mobile phase. The volume of extract injected was 20 μl. The present study determined the content of 15 priority PAHs from the US EPA priority pollutants list (US Environmental Protection Agency, 2020). Of these, the following are low molecular weight: 2-ringed (naphthalene) and 3-ringed (acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene), and high molecular weight: 4-ringed (fluoranthene, pyrene, benzo(a)anthracene, chrysene), 5-ringed (benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, dibenz(a,h)anthracene) and 6-ringed benz(g,h,i)perylene.

The extraction efficiency of target PAHs from soils was determined using the matrix method by constructing calibration curves. A fresh soil sample as well as an air-dry soil sample (1 g) were placed in a round bottom flask and a standard solution of PAHs in acetonitrile was added to target PAH concentrations of 2, 4, 6, 8, 16 or 32 μg kg^{-1}. After evaporating the solvent for 30 min under a fume hood, the PAH-added soil samples were incubated for 24 h at 4 °C. The samples were then analysed by the saponification method described above, followed by HPLC analysis.

Quality control of each detection by HPLC was performed according to Agilent Application Solution (Procedure of Measurements, 2008; Sushkova et al., 2024). Individual standard solutions were purchased from Sigma-Aldrich (Merch) (Burlington, MA, USA). A calibration standard of the PAH mixture was injected after every six samples to correct for retention time drift during the analysis. After plotting the calibration curve, a detection coefficient was calculated for each detected PAH:

The PAH content in the tested samples was determined by the external standard method. The PAH content in soil was calculated using the equation (1):

$$Cs = k\ Si \times Cst \times V/(Sst \times m), \qquad (1)$$

where Cs is the PAH content in the soil sample (μg kg^{-1}); Sst and Si are the areas of PAH peaks for standard solution and sample, respectively; Sst is the concentration of PAH standard solution (μg kg^{-1}); k is the PAH extraction factor from the sample; V is the volume of acetonitrile extract (ml); m is the mass of the sample (g).

Certified reference materials and calibration curves were used to calculate the limits of detection and limits of quantification, which were 2-200 μg kg^{-1}. For the developed methods for the isolation of target PAHs in soil, the random component of the measurement error was estimated, which was 3.5-14 % for the concentration range of 2-200 μg kg^{-1}.

Solvents and reagents were of HPLC purity and included ethanol (96%, p.a.) (Aquatest, Rostov-on-Don, Russia), n-hexane (99%, p.a.) (Aquatest, Rostov-on-Don, Russia), potassium hydrate (98%, p.a.) (Aquatest), acetonitrile (99.9%, p.a.) (Kriochrome, St. Petersburg, Russia), NaOH (97%, p.a.) (Kriochrome, St. Petersburg, Russia). (Aquatest), acetonitrile (99.9%, b.w.a.) (Cryochrom, St. Petersburg, Russia), NaOH (97%, b.w.a.) (Aquatest) and anhydrous Na_2SO_4 (Aquatest, Rostov-on-Don, Russia). A total of 15 priority PAH standards in acetonitrile with a concentration of 200 μg/cm^3 manufactured by Merch Burlington, MA, USA (NIST® SRM® 1647f Priority PAH Contaminants (in acetonitrile)) were used to prepare standard solutions of total PAHs for HPLC analysis. Analytical standards were purchased from Sigma-Aldrich (Merch) and used as an internal analytical standard.

Results

The average concentrations of PAHs in soils within the power plant's impact zone during the 2012–2022 monitoring period are presented in Figure 2. Over this decade, the mean total concentration of 15 priority PAHs increased by a factor of 1.6—from 661 ng/g in 2012 to 1089 ng/g in 2022. A sharp increase in the total content of PAHs was observed in 2016, corresponding to increased pollutant emissions from the plant in 2014–2015 (Sushkova et al., 2020; Sushkova et al., 2021; Chaplygin et al., 2023).

The formation of a contamination zone around industrial facilities for organic pollutants such as PAHs is regulated by the interaction of two opposing processes: (1) sorption and accumulation, and (2) migration, biodegradation, and biotransformation (Lodygin et al., 2021). PAHs from both point and linear emission sources are deposited onto soil surfaces adsorbed onto silty soil particles (Singh and Singh, 2025). Their retention is enhanced by soil sorption capacity, which depends on physical clay content and organic matter (Dudnikova et al., 2025).

The dispersion of PAHs occurs mainly due to microbial degradation by polyarene-degrading microorganisms, a process accelerated under aerobic conditions (Premnath et al., 2021). As semi-volatile compounds, PAHs—particularly low-molecular-weight congeners—evaporate from soil surfaces during summer months. When they evaporate, they are also subject to photodegradation. Within the soil environment, PAH molecules exist in dynamic equilibrium between the soil solution and the solid phase, balance determined by both soil properties and the physicochemical characteristics of individual PAHs (Singh and Singh, 2025).

Soil systems naturally tend toward equilibrium, with PAH dynamics conducted by competing processes of accumulation and dissipation (via biodegradation and migration). These mechanisms are inversely coupled: an increase in one leads to a suppression of the other. Critically, the behavior of PAHs in soils is jointly regulated by (1) emission source characteristics and (2) ecosystem-specific conditions—two largely independent sets of variables.

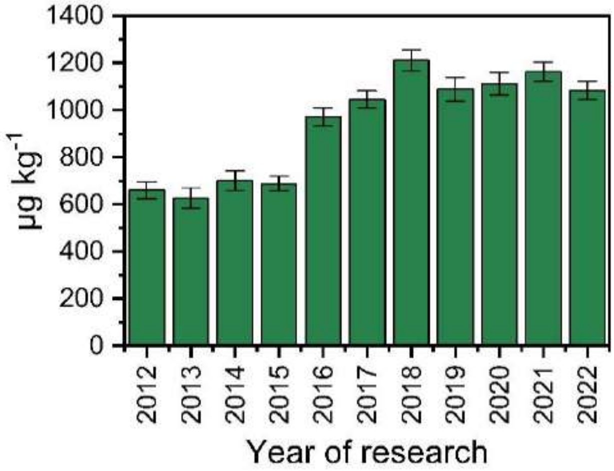

Figure 2. Average PAHs concentrations in soils of the power plant impact zone during 2012–2022

Using Spearman's correlation coefficient (at $p < 0.05$), it was shown that the total PAHs content increases over time. For soils at all monitored sites, the temporal increase in PAHs concentrations from 2012 to 2022 was most pronounced for anthracene, benzo[k]fluoranthene, and dibenz[a,h]anthracene (Table 2).

Table 2. Correlation between the concentrations of individual PAH compounds and their total content in soil, based on Spearman's correlation coefficient.

PAH	Correlation coefficient	PAH	Correlation coefficient
Naphthalene	0.04	Fluoranthene	0.49
Anthracene	0.61	Chrysene	0.32
Acenaphthene	0.33	Benzo[a]pyrene	0.30
Acenaphthylene	0.42	Benzo[b]fluoranthene	0.42
Fluorene	0.28	Benzo[k]fluoranthene	0.55
Phenanthrene	0.33	Dibenz[a,h]anthracene	0.51
Benz[a]anthracene	0.31	Benzo[ghi]perylene	0.30
Pyrene	0.48	Sum of 15 PAHs	0.47

Analysis of the 2012–2022 monitoring period revealed preferential accumulation of 15 priority PAHs in soils along the northwest axis from the power plant, aligning with the prevailing wind direction (Figure 3). A clear technogenic impact gradient was established:

1. Primary impact zone (NW direction from plant)
2. Proximal zone (1–3 km radius)
3. Distal zone (5–12 km radius)

In 2012, PAHs concentration in the 0–20 cm soil layer showed a spatial variability:

- Primary zone: 510–1060 ng/g (peak at Site 4, 2 km NW)
- Proximal zone: 431–739 ng/g
- Distal zone: 386–470 ng/g

These values substantially exceeded the regional background levels (<300 ng/g; Dudnikova et al., 2023; Sushkova et al., 2021). The spatial distribution pattern reflected atmospheric transport of ash particles via dominant southeast winds (Eren et al., 2024; Kasimov et al., 2024).

4. Temporal Concentration Trends

By 2022, all monitoring sites showed increased PAH concentrations:

- Primary zone: 1.5–2.3× increase (1050–3709 ng/g)
- Proximal zone: 1.1–2.2× increase (705–1361 ng/g)
- Distal zone: 1.5–1.7× increase (651–705 ng/g)

Global industrial comparative zones of PAHs monitoring demonstrated similar contamination patterns:

- 6000 ng/g (19 PAHs) near Australian coal mines (Idowu et al., 2020)
- 1000 ng/g (17 PAHs) near French gas plants (Biache et al., 2017)

- 900 ng/g (12 PAHs) near Russian thermal plants (Yakovleva et al., 2021)
- 6000 ng/g (13 PAHs) in Kuzbass coal fields (Ismagilov et al., 2018)

While Novocherkassk Power Plant soils (3709 ng/g peak) showed the lower contamination than extreme territories (e.g., Australian/Russian coal mines), they constantly exceed background thresholds. This confirms the persistent influence of power factories on soil PAHs concentrations, particularly under sustained emissions and unfavorable meteorological regimes.

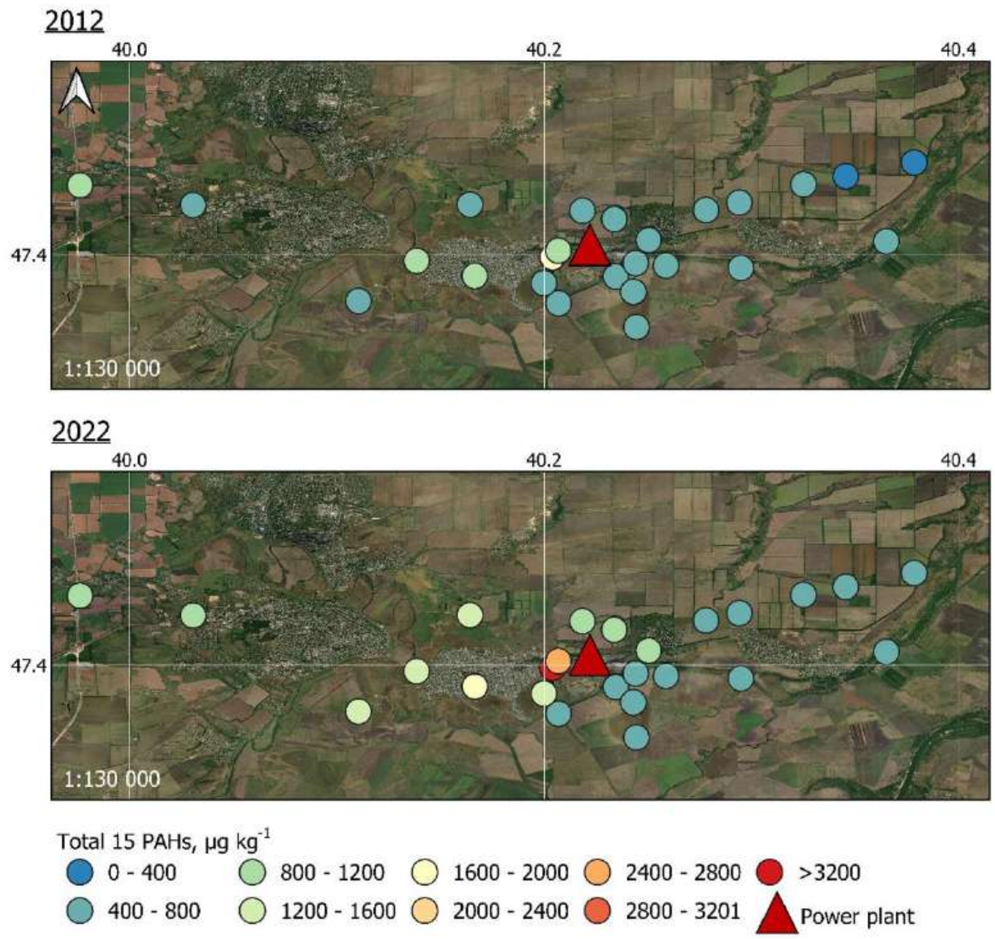

Figure 3. Spatial distribution of the total concentration of 15 priority PAHs in soils

According to the results of multifactorial analysis of variance, PAH concentrations in soil vary significantly depending on both the sampling location and the year of sample collection. A marked increase in the concentrations of all PAHs studied was observed over the 10-year monitoring period. This effect is more expressed for low-molecular-weight compounds, which are less stable in the environment, particularly in soils located along the prevailing wind direction to the northwest of the factory. This trend reflects the fact that, with increasing anthropogenic pressure, pollutant accumulation processes prevail on the dissipation processes.

Discussion

The data found in this study demonstrates significantly elevated PAHs concentrations in soils to the northwest from the power plant compared to ajacent territories, particularly for 4-ring compounds and the 6-ring benzo[ghi]perylene (Figure 2). This spatial distribution pattern reveals increased concentration gradients, with marked differences observed between soils at 1-3 km and 5-12 km from the facility, especially for chrysene and benzo[a]pyrene.

The observed PAH distribution patterns can be divided to the two principal factors: (1) atmospheric transport dynamics from the emission source, and (2) the physicochemical properties of ash particles serving as PAH carriers. As demonstrated by Gennadiev et al. (2020), PAHs are primarily deposited onto soil surface through aerosol emissions, with the organic fraction of soot exhibiting particularly strong PAH affinity (Lammel, 2015). Combustion of solid fuels typically generates aerosols ranging 0.1-10 μm (Kliucininkas et al., 2014), with

Zhang et al. (2015) reporting that most PAHs are associated with submicron particles (<1 μm), though seasonal variations between summer and winter may affect this distribution (Wang et al., 2024).

The transport mechanisms of PAHs-absorbing particles exhibit size-dependent characteristics:

- Particles 0.1-3 μm can be distributed up to 100 km (Chin et al., 2007), that is explaining their presence in the background soils
- Submicron particle-associated PAHs concentrations decreased with increasing of the distance from emission source (Zhang et al., 2020)
- Atmospheric deposition is characterised by:

(i) Dry/wet deposition (3-5 μm particles)

(ii) Particle coagulation (0.1-3 μm particles) (Abdel-Shafy and Mansour, 2016)

Notably, combustion processes affect PAHs distribution by different way:

- Peat combustion promotes surface coagulation of high-molecular-weight PAHs
- Low-molecular-weight PAHs predominantly remain in gas phase (Samburova et al., 2016)

Particle size significantly influences PAH distribution:

- 50-90% of total PAHs are associated with <0.5 μm particles (Lammel, 2015)
- Ultrafine particles preferentially concentrate ≥6-ring PAHs (Zhang et al., 2020)
- Increasing particle size (0.95→3 μm) reduces 2-ring PAH proportion (Landlova et al., 2014)
- PAH ratios in 0.5 μm fraction reflected combustion quality (Kliucininkas et al., 2014)

As demonstrated by Wu et al. (2006), dispersion radius correlates inversely with particle size and directly with wind direction stability. In industrial settings, this typically results in elongated pollution areas located at the prevailing winds direction rose (Williams, 2013), consistent with observed northwestward contamination gradient.

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Remote sensing-based assessment of coastal erosion and geomorphological changes in a Caspian delta

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Abstract

The Kura River Delta is a dynamic coastal system affected by both marine and fluvial processes. Understanding the geomorphological changes in this region is crucial for sustainable coastal management. This study aims to analyze the geomorphological dynamics of coastal erosion in the Kura River Delta over the past 35 years (1985–2020), identify transformation processes, and evaluate the main drivers using satellite data. High-resolution Landsat 5, Landsat 8, and Sentinel-2 imagery were used. Atmospheric and geometric corrections were applied using ENVI and ArcGIS. The Digital Shoreline Analysis System (DSAS) was employed for shoreline displacement analysis. NDVI, MNDWI, and Tasseled Cap Transformation indices were calculated for land-water classification and landscape dynamics. The results indicate that Caspian Sea level fluctuations and Kura River discharge variability have caused both seaward and landward shoreline shifts. Significant geomorphological changes include erosion–accumulation shifts, coastal terrace reformation, and fragmentation of land cover. The total area affected by transformation was estimated at 48.1 km^2. Remote sensing and GIS technologies prove to be essential for monitoring coastal erosion and supporting sustainable management practices in vulnerable deltaic systems.

Key words: coastal erosion; shoreline change; remote sensing; DSAS; Caspian Sea level; landscape transformation; climate action

Introduction

High river deltas are highly dynamic environments subjected to a broad spectrum of natural and anthropogenic influences. The Caspian Sea's connection to the ocean is limited, and its level fluctuations cover a wide range (Figure 1). Such level changes cause intense geomorphological mobility in deltas like those of the Volga and Kura Rivers. Consequently, addressing issues related to infrastructure planning, land cover management, settlement expansion, and ecosystem conservation in the Kura River delta requires comprehensive monitoring of geomorphological changes occurring in both the river and coastal zones.

Recently, mismanagement in water use has led to critical water shortages in the Kura River, with the construction of regulators (Ana and Bala Kura) further impacting the delta's geomorphology. These intensive anthropogenic pressures, coupled with natural processes, necessitate continuous, precise monitoring of the delta's geomorphological dynamics, which cannot be achieved solely by traditional topographic measurements. The Kura delta lies at the interface of the atmosphere, hydrosphere, lithosphere, and biosphere, and its coastal zones feature diverse geomorphological landscapes shaped by processes such as erosion and accumulation.

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This study focuses on analysing the spatiotemporal dynamics of coastal erosion and sediment accumulation in the Kura delta from 1985 to 2020, using high-resolution remote sensing data and advanced analytical methods such as Tasselled Cap Transformation and the Digital Shoreline Analysis System (DSAS).

Material and Methods

Study Area

The Kura delta, located within the Azerbaijani sector of the Caspian Sea near the Salyan district, spans approximately 87.92 km of coastline, extending from the collector drainage network (49°17'19.521"E, 39°33'5.539"N) to the Mughan-Salyan Canal (49°14'27.13"E, 39°17'39.548"N). The delta is characterized by depositional landforms shaped by riverine and marine processes.

Data Acquisition and Processing

Satellite imagery from Landsat 5, Landsat 8, and Sentinel-2 spanning 1985–2020 was utilized. Images underwent atmospheric and geometric corrections using ENVI and ArcGIS software. Vegetation, water, and bare soil classification were performed using indices such as the Normalized Difference Vegetation Index (NDVI) and the Modified Normalized Difference Water Index (MNDWI) (1.2).

$$NDVI = \frac{NIR - Red}{NIR + Red} \qquad (1)$$

$$MNDWI = \frac{Green - SWIR}{Green + SWIR} \qquad (2)$$

Tasseled Cap Transformation (TCT) was applied to distinguish soil and water surfaces more accurately. Shoreline extraction was conducted through semi-automated classification, and the Digital Shoreline Analysis System (DSAS) was employed to quantify shoreline changes with 300 m interval transects perpendicular to the coast (Figure 1.).

Figure 1. Geographical position of the coastline in 1985-2020

Results

The analysis revealed significant shoreline migration between 1985 and 2020, with periods of both accretion and erosion observed (Figures 2–3). The shoreline advanced seaward on average by 345.5 m during the entire study period, with the highest erosion rates recorded during intervals of Caspian Sea level decline.

Spatial analysis of delta morphology indicated that coastal erosion dominates in several segments, resulting in a net loss of approximately 31.18 km^2 during periods of sea-level rise, while sediment accumulation led to an increase of 16.9 km^2 during sea-level fall (Figure 2).

Figure 2. Evolution of the delta for 1985-2020.

A strong correlation was found between Caspian Sea level fluctuations and shoreline dynamics (Figure 6). For instance, from 1977 to 1996, rising sea levels (correlation coefficient 0.82) intensified erosional processes, while subsequent stabilization and decline (1996–2019, correlation coefficient -0.46) favoured sediment deposition.

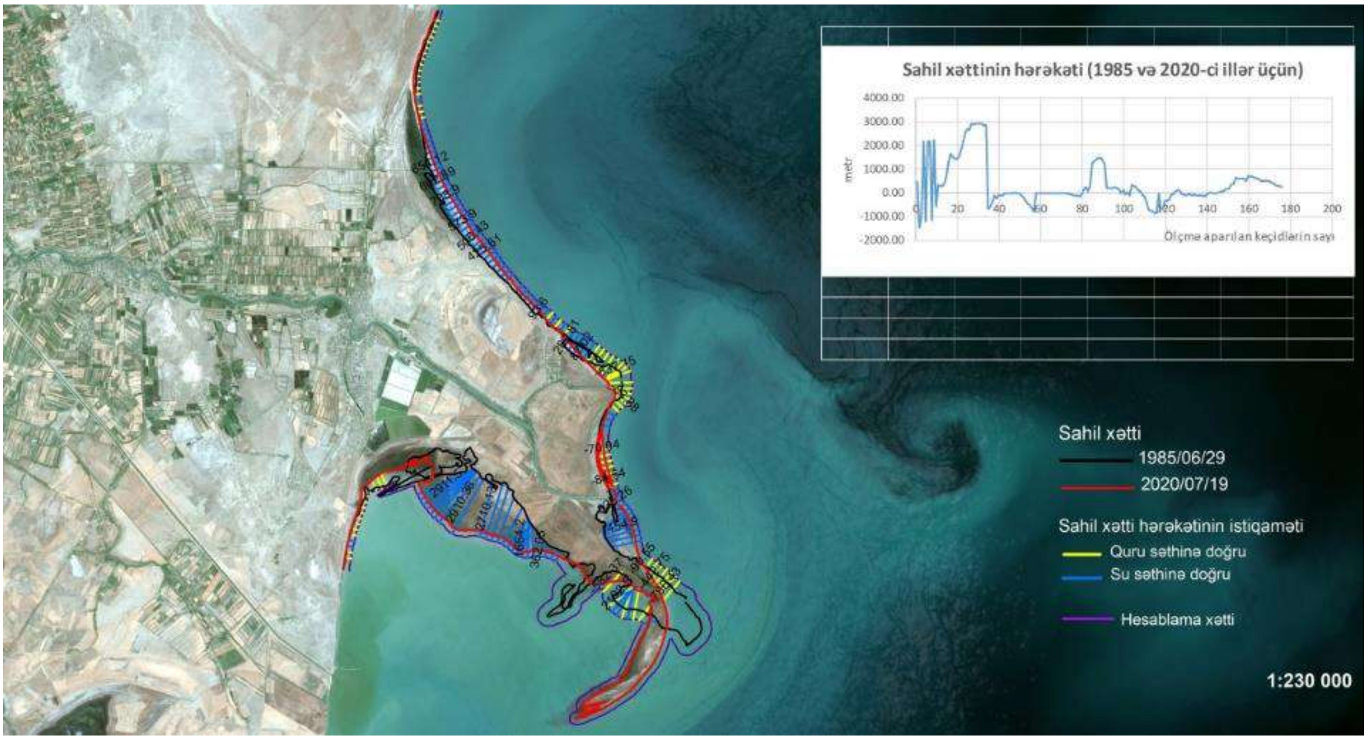

Figure 3 . Coastline erosion in 1985 and 2020

Discussion

The findings underscore that coastal erosion in the Kura delta is driven by complex interactions of climatic, hydrological, tectonic, and anthropogenic factors. Climate-induced changes in river discharge, precipitation, and evaporation alone cannot explain the observed long-term shoreline dynamics. Seismic activity related to the South Caspian Plate margin also appears to influence sea level variability, contributing to episodic erosional events.

Moreover, human interventions such as dam and regulator construction alter sediment supply and hydrodynamics, exacerbating erosion in certain delta sections. This highlights the critical need for integrated coastal zone management incorporating remote sensing-based monitoring to guide sustainable infrastructure development and ecosystem protection in deltaic environments. The Caspian Sea level fluctuation directly affects the changes in the delta area (Figure 6). The last minimum sea level in the Caspian Sea was recorded in 1977 at -29 m. Starting from 1977, the sea level rose and reached -26.66 m in 1955, after which the sea level decreased by 50 cm in 1980 and then remained practically stable since 2003 and then increased by 30 cm until 2005 to -26.8 m. Since 2005, the level has decreased by 8-10 cm with very small fluctuations (Figure 3).

Figure 3. Relationship between the change in the level of the Caspian Sea and the area and perimeter of the Kura delta

The application of tools like DSAS and spectral indices proves essential in understanding coastal transformations and guiding effective erosion mitigation strategies. This also supports global efforts to sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, in line with the United Nations Sustainable Development Goals (SDG 14.2). Future research should focus on integrating hydrodynamic modeling and socio-environmental factors to enhance coastal resilience planning.

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Effect of cultivation factors on rice productivity elements in the Lankaran-Astara region of Azerbaijan

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Abstract

This study investigates the effect of different sowing dates, varying NPK fertilizer application rates, and seed quantities on rice productivity and soil nutrient content in the pseudopodzolic soils of the Lankaran-Astara region under natural climatic conditions. Experiments conducted between 2016-2019, focusing on the "Haşimi" rice variety, were carried out using a randomized complete block design with four replications in the region's unique pseudopodzolic clayey-yellow soils. The results show a significant positive correlation between nitrogen application and rice yield. Specifically, the treatment 1.7-N120P80K60 (1.7 million seed rate, 120 kg N/ha, 80 kg P/ha, and 60 kg K/ha) demonstrated the highest average rice yield. Agrochemical analyses conducted under the conditions of Lankaran district show that these soils are not adequately supplied with nutrients. Therefore, proper fertilization is essential for the growth and development of rice plants, achieving high-quality yields, and maintaining soil fertility in these soils.

Key words: Rice productivity, nitrogen application, soil analysis

Introduction

Rice, being a major staple crop, is consumed by half of the world's population. For high yields to be formed, all conditions must be optimal. Many scientists note that the height of the plant, the number of productive stems, and the duration of the growing season are key agronomic indicators that, when interrelated, increase the rice yield (Lei L. et al., 2018). Currently, rice is cultivated on 155 million hectares in 112 countries, with an annual production of 600 million tons. According to FAO data, the demand for rice exceeds that for wheat by 2.3%, and the current productivity does not meet this demand (S. Pandey et al., 2010).

Rice is a primary food source for more than 3 billion people worldwide, including nearly 60% of China's population. To meet the growing population's demand, rice production must be increased. However, the available natural land resources for cultivation are limited. Therefore, much of this growth must come from increasing yield per hectare. Nitrogen (N) is one of the key factors affecting rice yield and has been excessively used in China (Zhang QW. et al., 2012).

Improper fertilization systems and excessive nitrogen fertilizer use have resulted in significant nitrogen loss due to ammonia (NH_3) volatilization and leaching (Cao YS. et al., 2013). Some effective measures have been recommended to reduce nitrogen rates (Islamzade et al., 2024), such as nitrogen application in the later growth stages, applying the required nitrogen fertilizer (Yang YC. et al., 2012), planting high-yielding rice varieties (Zhu G. et al., 2016), and using a combination of organic and mineral fertilizers (Wen ZH. et al., 2016). The timing and rates of fertilizer application play a crucial role in plant growth and nutrient absorption

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(Islamzade et al., 2023; Sun L. et al., 2012). The main goal of this study is to develop efficient cultivation methods for obtaining high and quality rice yields from paddy fields in the Lankaran-Astara region's clayey-yellow (pseudopodzolic) soils, focusing on the timing of transplanting seedlings, the seedling density per hectare, and the nutrition conditions.

Material and Methods

Field experiments were conducted from 2016 to 2018 at "Janub Agro LLC" located in the Siyavar village of the Lankaran region, on clayey-podzolic-yellow soils. The experiments were carried out with rice variety, "Hashimi" . The experiments were set up during the first and third decades of May, according to the following scheme:

Table 1. Scheme of the experimental field

Treatments	Seed Rate (million/ha)	Nitrogen fertilizer rate (kg/ha)	Phosphorus fertilizer rate (kg/ha)	Potassium fertilizer rate (kg/ha)
1.0-$N_0P_0K_0$	1.0	0	0	0
1.0-$N_{90}P_{60}K_{40}$	1.0	90	60	40
1.0-$N_{120}P_{80}K_{60}$	1.0	120	80	60
1.7-$N_0P_0K_0$	1.7	0	0	0
1.7-$N_{90}P_{60}K_{40}$	1.7	90	60	40
1.7-$N_{120}P_{80}K_{60}$	1.7	120	80	60
2.5- $N_0P_0K_0$	2.5	0	0	0
2.5- $N_{90}P_{60}K_{40}$	2.5	90	60	40
2.5- $N_{120}P_{80}K_{60}$	2.5	120	80	60

The area of each experimental plot was 54.0 m^2 (30x1.80 m), and the prepared seedlings were planted using a row method in four replications. Mineral fertilizers included nitrogen-ammonium nitrate (34.7%), phosphorus-simple superphosphate (18.7%), and potassium-potassium sulfate (46%). Phosphorus and potassium were applied at 100%, while nitrogen was applied at 50% before planting the seedlings into the soil, under plowing. The remaining 50% of nitrogen was applied in the form of top dressing during the tillering phase, between the rows. Phenological observations were conducted with 10 plants, and agronomic practices were carried out according to the accepted guidelines for the region. Before planting the rice seedlings, soil samples were collected from five different points in the field using the core method at depths of 0-25, 25-50, and 50-70 cm, and the main agrochemical indicators were determined. The statistical analysis of the field experiment and laboratory results was processed using the SPSS26 software.

Soil Analyses: Following the methods outlined by Rowell (1996) and Jones (2001), mineral nitrogen (NH_4 and NO_3), available phosphorus, and exchangeable potassium contents were determined through 1 N KCl extraction and 1% $(NH_4)_2CO_3$ extraction from the soil samples. These analyses facilitated the assessment of the impacts of different NPK fertilizer dosages and varying levels of barley planting on the soil's capacity to supply plant-available nitrogen, phosphorus, and potassium. These insights contribute to a comprehensive understanding of how different soil nutrient dynamics interact with barley growth and development during various growth stages, thereby enriching the interpretation of the experiment's outcomes.**

Results and Discussion

The agrochemical properties of the clayey-podzolic yellow soils at "Janub Agro LLC" in Siyavar village, Lankaran region, where the study was conducted, are presented in Table 2.3. To determine the agrochemical properties of the soil before setting up the experiment, the quantities of total and available forms of nutrients were determined in mixed soil samples taken from 0-25, 25-50, and 50-75 cm depths.

Table 2. Agrochemical properties of the experimental field soils

Depth	pH	Organic matter, %	Total N, %	NH4-N, mg/kg	NO3-N, mg/kg	Available P, mg /g	Exchangeable K2O, mg/kg
0-25	5.2	3,12	0,17	35,3	7,6	35,6	185,5
25-50	5.4	2,55	0,15	30,2	5,2	24,3	156,0
50-75	5.6	1,56	0,12	15,5	3,5	10,2	123,6

As seen from the table, the pH in water solution was 5.2 in the 0-25 cm layer, 5.4 in the 25-50 cm layer, and 5.6 in the 50-75 cm layer. The humus, total nitrogen, phosphorus, and potassium contents in the 0-25 cm layer were 3.12%, 0.17%, 0.28%, and 2.28%, respectively. In the 25-50 cm layer, they were 2.55%, 0.15%, 0.25%, and 2.53%, respectively. These values decreased in the deeper layers, with the 50-75 cm layer having 1.56%, 0.12%, 0.18%, and 2.21%, respectively.

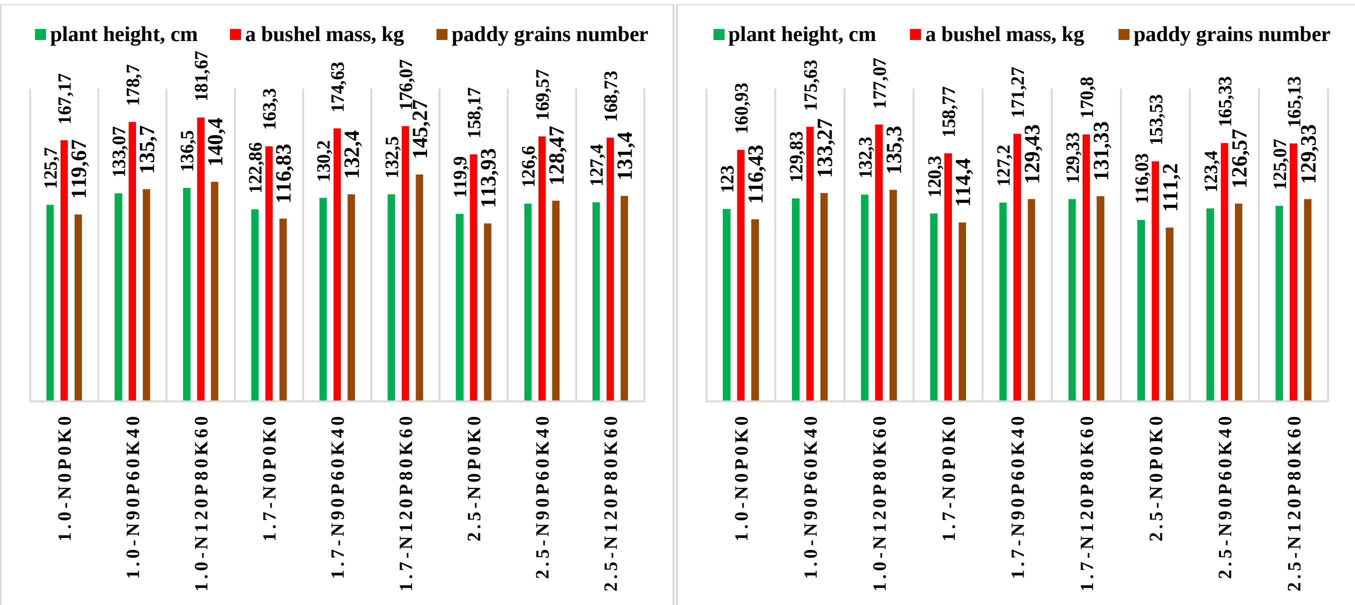
The available ammoniacal nitrogen was 35.3-15.5 mg/kg for the 0-25 and 50-75 cm layers, nitrate nitrogen was 7.6-3.5 mg/kg, available phosphorus ranged from 35.6 to 24.3 mg/kg, and exchangeable potassium varied from 185.5 to 123.6 mg/kg.

Thus, the agrochemical analysis carried out in the Lankaran region shows that these soils are not sufficiently supplied with nutrients. Therefore, proper fertilization is extremely important for the growth and development of rice, for achieving high and quality yields, and for maintaining soil fertility in these areas.

The effect of transplanting time, seedling density per hectare, and nutritional conditions on the structural elements of the "Haşimi" rice variety was studied in 2016-2018. In the first decade of May, in the control (no fertilizer) variant with a seedling density of 1.0 million per hectare, at the end of the vegetation period, the rice height was 125.7 cm, the mass of one plant was 167.17 g, the mass of one panicle was 28.10 g, the tillering index was 20.13 plants, the length of the panicle was 26.10 cm, the number of grains per panicle was 119.67, and the weight of 1000 grains was 26.17 g. As the seedling density per hectare increased, each of the studied indicators decreased.

In the control (no fertilizer) variant with a seedling density of 1.7 million per hectare, at the end of the vegetation period, the rice height was 122.83 cm, the mass of one plant was 163.3 g, the mass of one panicle was 25.77 g, the tillering index was 17.9 plants, the length of the panicle was 24.4 cm, the number of grains per panicle was 116.83, and the weight of 1000 grains was 25.3 g.

The lowest values for structural elements were observed in the control (no fertilizer) variant with a seedling density of 2.5 million per hectare. This can be explained by the fact that each seedling had less available space for nutrition. In the variant with a seedling density of 2.5 million per hectare, at the end of the vegetation period, the rice height was 119.9 cm, the mass of one plant was 158.17 g, the mass of one panicle was 22.87 g, the tillering index was 16.0 plants, the length of the panicle was 22.87 cm, the number of grains per panicle was 113.93, and the weight of 1000 grains was 24.1 g.



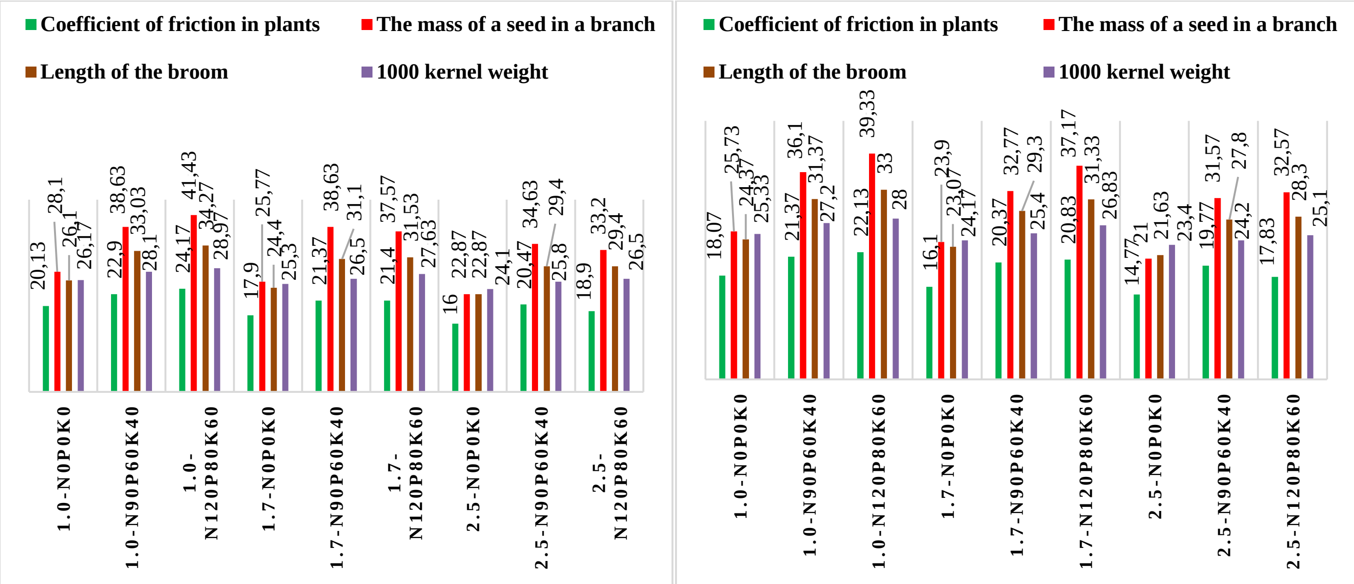
	F value		
Seed rate	10.091***	25.144***	125.290***
Fertilizer norms	15.012***	12.271***	20.396***
Planting time	6.093***	6.903***	19.945***

Figure 1. Dependence of the structural indicators of the rice plant on the sowing and fertilizer rates in the first and third decades of May

In the variant with seedlings planted in the third decade of May and a seedling density of 1.0 million per hectare (control, no fertilizer), at the end of the vegetation period, the rice height was 123.0 cm, the mass of one plant was 160.93 g, the mass of one panicle was 25.73 g, the tillering index was 18.07 plants, the length of the panicle was 24.37 cm, the number of grains per panicle was 116.43, and the weight of 1000 grains was 25.33 g. As the seedling density per hectare increased, as seen in the first decade, each of the studied indicators decreased.

In the control (no fertilizer) variant with a seedling density of 1.7 million per hectare, at the end of the vegetation period, the rice height was 120.3 cm, the mass of one plant was 158.77 g, the mass of one panicle was 23.9 g, the tillering index was 16.1 plants, the length of the panicle was 23.07 cm, the number of grains per panicle was 114.4, and the weight of 1000 grains was 24.17 g.

The lowest values for the structural elements were observed in the control (no fertilizer) variant with a seedling density of 2.5 million per hectare. This can be explained by the fact that each seedling had less available space for nutrition. In the variant with a seedling density of 2.5 million per hectare, at the end of the vegetation period, the rice height was 116.03 cm, the mass of one plant was 153.53 g, the mass of one panicle was 21.0 g, the tillering index was 14.77 plants, the length of the panicle was 21.63 cm, the number of grains per panicle was 111.2, and the weight of 1000 grains was 23.4 g.



	F value			
Seed rate	26.165***	596.727***	25.567***	53.216***
Fertilizer norms	9.953***	104.873***	1.216***	53.364***
Planting time	3.771***	44.786***	6.703***	29.369***

Figure 2. Yield components of rice plants in the first and third decades of May

When seedlings were planted in the first decade of May, in the variant with 1.0 million seedlings per hectare ($N_{90}P_{60}K_{40}$), at the end of the vegetation period, the rice height was 133.07 cm, the mass of one plant was 178.7 g, the mass of one panicle was 38.63 g, the tillering index was 22.9 plants, the length of the panicle was 33.03 cm, the number of grains per panicle was 135.7, and the weight of 1000 grains was 28.1 g.

In the variant with 1.7 million seedlings per hectare ($N_{90}P_{60}K_{40}$), at the end of the vegetation period, the rice height was 130.2 cm, the mass of one plant was 174.63 g, the mass of one panicle was 36.93 g, the tillering index was 21.37 plants, the length of the panicle was 31.1 cm, the number of grains per panicle was 132.4, and the weight of 1000 grains was 26.5 g.

The lowest values for the structural components were observed when the seedling density per hectare was 2.5 million in the $N_{90}P_{60}K_{40}$ variant. At the end of the vegetation period, the rice height was 126.6 cm, the mass of one plant was 169.57 g, the mass of one panicle was 34.63 g, the tillering index was 20.47 plants, the length of the panicle was 29.40 cm, the number of grains per panicle was 128.47, the number of panicles was 8.8-9.0, and the weight of 1000 grains was 25.8 g.

In the planting carried out in the third decade of May, the structural components in both the control and $N_{90}P_{60}K_{40}$ variants were lower compared to those observed in the first decade of May.

In comparison to the $N_{90}P_{60}K_{40}$ variant, in the $N_{120}P_{80}K_{60}$ variant, the structural components of rice plants were higher for all planting periods and seedling densities, which ultimately affected the yield. When seedlings were planted in the first decade of May, in the variant with 1.0 million seedlings per hectare ($N_{120}P_{80}K_{60}$), at the end of the vegetation period, the rice height was 136.5 cm, the mass of one plant was 181.67 g, the mass of one panicle was 41.43 g, the tillering index was 24.17 plants, the length of the panicle was 34.27 cm, the number of grains per panicle was 140.4, and the weight of 1000 grains was 28.97 g.

In the variant with 1.7 million seedlings per hectare ($N_{120}P_{80}K_{60}$), at the end of the vegetation period, the rice height was 132.5 cm, the mass of one plant was 176.07 g, the mass of one panicle was 37.57 g, the tillering index was 21.4 plants, the length of the panicle was 31.53 cm, the number of grains per panicle was 145.27, and the weight of 1000 grains was 27.63 g.

The lowest values for the structural components were observed in the $N_{120}P_{80}K_{60}$ variant with a seedling density of 2.5 million per hectare. At the end of the vegetation period, the rice height was 127.4 cm, the mass of one plant was 168.73 g, the mass of one panicle was 33.2 g, the tillering index was 18.9 plants, the length of the panicle was 29.4 cm, the number of grains per panicle was 131.4, and the weight of 1000 grains was 26.5 g. The structural components were lower in the third decade of May compared to those in the first decade of May.

Conclusion

Thus, when seedlings were planted in the first planting period, in the Haşimi variety of rice, the structural components of the plant were higher at all three planting densities, while they decreased in the second planting period. The highest values were observed when seedlings were planted in the first decade of May, in a variant with a seedling density of 1.0 million per hectare and a fertilizer dose of $N_{120}P_{80}K_{60}$. The lowest values were found in the variant with a higher plant density of 2.5 million seedlings per hectare and fertilizer dose $N_{120}P_{80}K_{60}$.

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Investigation of the effects of different doses of ammonium sulfate, diammonium phosphate, urea and 15-15-15 NPK fertilizer applications on pH and nutrient elements in agricultural soils taken from different regions

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Abstract

Plant nutrition is a crucial issue in both our country and global agriculture. Fertilization methods and fertilizer selection for plant nutrition are considered highly sensitive issues today. Fertilizers are categorized under two main categories: organic and chemical. Chemical fertilizers are used inappropriately in today's agriculture. Excessive use of chemical fertilizers not only affects the absorption of other nutrients in the soil but also affects important soil properties such as soil pH and nutrient levels. This effect is thought to vary depending on the type and amount of fertilizer used. In this study, ammonium sulfate, DAP, urea, and 15-15-15 NPK fertilizers were applied at doses of 0, 10, and 20 kg da-1 to soil samples taken from agricultural lands in the provinces of Kayseri and Adana. The study aimed to determine the effects of chemical fertilizers, commonly used as base and top dressing fertilizers, on existing soil properties when applied to cultivated areas and to identify any differences that may occur in agricultural lands

Keywords: Fertilization, Soil, pH, Fertilizer, Nutrient Element.

Introduction

In our country, population and consumption are increasing in parallel. To meet the emerging consumption surplus without external dependence, increasing yield per unit area and ensuring high quality products are essential. Therefore, improving yield and quality levels has become a priority for many researchers. Fertilizers and fertilization, a topic that has been around for centuries, are also popular for improving yield and quality parameters. Fertilization increases yield in agricultural production and ensures high-quality products (Savci, S. 2012). Fertilizers are generally classified as organic and inorganic. Chemical fertilizer applications are known to affect many physical, chemical, and biological properties of soils beyond simply maintaining or increasing yields (Belay et al., 2002). These effects of fertilizers are believed to influence soil quality and fertility levels over long periods of time (Acton and Gregorich 1995). In addition to the positive effects of fertilizers and fertilization, negative effects can also occur. Because when we examine the world, excessive use of chemical fertilizers is observed (Wan et al., 2021). Past studies have indicated that declines in soil quality and production rates may be observed due to the continued use of chemical fertilizers (Gliessman 1984; Doran and Werner 1990; Cassman and Pingali 1995; Doran et al. 1996). It is known that excessive chemical fertilizer applications negatively affect the physical and chemical properties of soils, leading to soil hardness and acidic reactions, as well as a decrease in organic matter content and yields (Gu et al. 2015; Lv et al. 2020). To ensure the sustainability of agricultural soils and to ensure that future generations can carry out agricultural

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production on the same soils, we must avoid all behaviors that negatively affect the properties of our agricultural soils.

The aim of this study is to determine the effects of ammonium sulphate, diammonium phosphate, urea and 15-15-15 NPK fertilizers applied at doses of 10 kg/da and 20 kg/da to the agricultural lands in Tufanbeyli district of Adana province and Talas district of Kayseri province on soil reaction, salinity and nutrient elements.

Material and Methods

This study is being conducted in 2025 in an open field at the study site of Erciyes University's Faculty of Agriculture, with a total of 54 ink columns, consisting of 16 treatments and 2 controls, with three replications.

Soil data were collected in two different regions. In this study, soil samples were taken from the Tufanbeyli district of Adana province, from agricultural land at coordinates 38°15'18.7"N 36°10'22.0"E, and soil samples were taken from the Talas region of Kayseri province, from agricultural land at coordinates 38°71’60.69”N and 35°54’77.05”E.

Soil samples taken from the different regions will be weighed in 1 kg doses. The chemical fertilizers to be applied were calculated according to 10 kg and 20 kg doses and mixed with the soil before being added to the incubation columns. The fertilizers used in the study were ammonium sulfate, diammonium phosphate, urea, and 15-15-15 NPK fertilizers. The fertilizers, homogeneously mixed with the soil, were treated in columns for 10 days and then sieved through a 2-mm sieve and placed in the Soil Analysis Laboratory of the Faculty of Agriculture at Erciyes University for analysis. pH, calcium, oxygen, and sodium contents were determined.

The preferred method for determining soil data was to treat the soil with water at a 1:2.5 ratio and measure the pH with a pH meter (Mclean 1982). For the determination of calcium, calcium, and sodium contents in the soils, soils treated with ammonium acetate were identified using an ICP-OES device (Rhoades 1982b). The fertilizers, application doses, and residues of the regions used in this study are shown in Table 1.

Table 1. Treatments abbreviations

Abbreviations	Region	Fertilizer type	Dosage (kg/da)
K:K	Kayseri	-	-
K:Ü1	Kayseri	Urea	10
K:Ü2	Kayseri	Urea	20
K:A1	Kayseri	Ammonium sulfate	10
K:A2	Kayseri	Ammonium sulfate	20
K:D1	Kayseri	Diammonium phosphate	10
K:D2	Kayseri	Diammonium phosphate	20
K:NPK1	Kayseri	15-15-15	10
K:NPK2	Kayseri	15-15-15	20
T:K	Adana	-	-
T:Ü1	Adana	Urea	10
T:Ü2	Adana	Urea	20
T:A1	Adana	Ammonium sulfate	10
T:A2	Adana	Ammonium sulfate	20
T:D1	Adana	Diammonium phosphate	10
T:D2	Adana	Diammonium phosphate	20
T:NPK1	Adana	15-15-15	10
T:NPK2	Adana	15-15-15	20

The statistical significance level of the data obtained in the study was subjected to variance analysis using the SPSS -13 package program, and the data discovered to be significant in the study were treated with the Duncan multiple comparison test (SPSS 2004).

Results and Discussion

Effects of fertilizers on soil pH

The effects of applying different doses of ammonium sulfate, diammonium phosphate, urea and 15-15-15 NPK fertilizers to soil samples taken from agricultural lands of Tufanbeyli and Talas districts on the pH values in the soil are given in Graph 1. According to the statistical analysis made in line with the data obtained as a result of the applications, it was determined that the difference between the applications and regions was statistically significant ($P<0.01$).

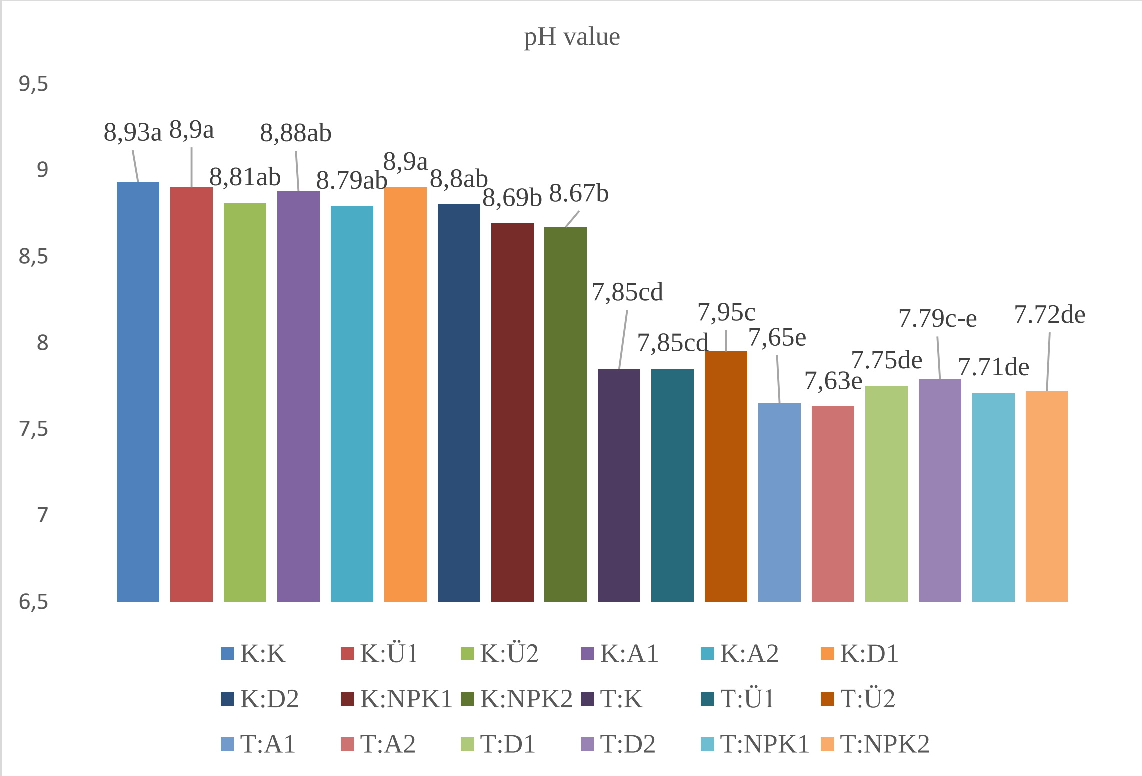

Figure 1. Effect of applications on soil pH

When we examined the effects of fertilizers applied to soils from different regions on lowering pH, ammonium sulfate fertilizer was found to have the greatest effect in soils from the Tufanbeyli district compared to control soils, while 15-15-15 NPK fertilizer was found to have the greatest effect in soils from the Talas district. Vasak et al. (2015) applied a fertilization system to trial fields in four different regions. Similar to our study, they experienced decreases in pH values due to regional differences. Similarly to our study, they determined that not all fertilizers have the same function in different soil characteristics.

Effects of fertilizers on calcium, magnesium and sodium contents in soil

The effects of different rates and types of fertilization applied to soil samples taken from two different regions on macro plant nutrients are shown in Table 2. The effects of the applications on calcium, magnesium and sodium rates were found to be statistically very significant ($p<0.01$)

Table 2. Effect of fertilizer applications on macronutrients

Treatments	Ca, mg/kg	Mg, mg/kg	Na, mg/kg
K:K	4424.00a	225,20b-d	46,45cd
K:Ü1	3606,40a -d	217,72cd	52,04cd
K:Ü2	3515,00a-d	205,34d	55,16cd
K:A1	3727,10a-d	217,92cd	64,85b-d
K:A2	3655,00a-d	219,00cd	71,40bc
K:D1	4413.00a	205,97d	53,36cd
K:D2	3831.00a-c	218,27cd	58,63b-d
K:NPK1	4291.00ab	231,94a-d	55,16cd
K:NPK2	3142.00a-d	192,00d	50,17cd
T:K	2214.00cd	282,40a-c	111,81a
T:Ü1	2204.00cd	281,80a-c	87,28ab
T:Ü2	1827.00d	233,50a-d	66,53b-d
T:A1	2308,70b-d	288,96ab	40,97d
T:A2	2399,00b-d	294,33a	39.86d
T:D1	2229,00cd	272,82a-c	43,46cd
T:D2	2029.00cd	251,20a-d	42,13cd
T:NPK1	2713.00a-d	290,56ab	44,95cd
T:NPK2	1955.00cd	247,50a-d	38,53d

When we examined the effects of chemical fertilizers applied at different rates and types to soils from different regions on macronutrient levels in the soil, we found that ammonium sulfate, urea, diammonium phosphate, and 15-15-15 NPK fertilizers applied to soils from the Talas district did not increase calcium compared to control soils. However, fertilizer applications applied to soils from the Tufanbeyli district increased calcium content compared to control soils when applied at 10 kg per decare of both ammonium sulfate fertilizer doses, diammonium phosphate fertilizer doses, and 15-15-15 NPK fertilizer doses.

Soil magnesium content was found to be lower compared to control soils when applied at 10 kg and 20 kg per decare of urea, ammonium sulfate, and diammonium phosphate fertilizer doses, and when applied only at 20 kg per decare of 15-15-15 fertilizer, the magnesium content in the soil was found to be lower than in the control soils. An increase in magnesium content was observed in Talas soils when applied at 10 kg per decare of 15-15-15 fertilizer compared to the control soils. The effects of fertilizer applications on magnesium content in the test soils taken from Tufanbeyli were found to be different compared to the Talas soils. Application of ammonium sulfate fertilizer at doses of 10 and 20 kg per decare and 15-15-15 NPK fertilizer at 10 kg per decare increased the magnesium content in the soil compared to the control soils. Increasing the application of urea fertilizer, one of the other applied fertilizers, was found to decrease the magnesium content in the soil compared to the control soils. It was determined that urea, ammonium sulfate, diammonium phosphate, and 15-15-15 compound fertilizer applied to soils taken from the Talas district, where soil reaction levels are high, increased the sodium content in the soil compared to the control soils. Fertilization applications applied to soils from the Tufanbeyli district, which has a lower pH compared to soils from other regions, were found to reduce the sodium content of the soil compared to the control soils. In their study, Baley et al. (2002) compared fertilizer applications with control applications, they observed that calcium and magnesium contents decreased, while sodium content increased only with the application of potassium-containing chemical fertilizers. When the results of the aforementioned studies were evaluated and compared with our own study, it was observed that while the results were similar in terms of calcium content in the soil, the effects of fertilizers on magnesium content were different. When we evaluated sodium content, it was observed that the effectiveness of fertilizers applied to soils from the Talas district increased sodium content compared to the control soils, while the same applications showed that fertilizers applied to Tufanbeyli soils, which have a lower pH, reduced sodium content compared to the control soils.

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The Effect of Cover Crops on Wet Aggregate Stability, Dispersion Ratio and Organic Matter of Soil in *Nigella Sativa* L.

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Abstract

Cover crops play an important role in improving soil structure and organic matter and contribute to sustainable agricultural practices. They also increase organic matter through decomposition of plant residues, contribute to humus formation and support microbial activity, thus promoting overall soil health.In this study, the effects of different cover crops on wet aggregate stability (WAS), dispersion ratio (DR) and organic matter (SOM) of soil were investigated in the field where *Nigella Sativa* L. seed was grown at Erciyes University Agricultural Research and Application Centre in Kayseri, Türkiye. *Vicia sativa* L. (VS), *V. sativa* L. + *Hordeum vulgare* L. (VS+HV), *V. villosa* Roth. (VV), *V. villosa* Roth. + *H. vulgare* L. (VV+HV), *Secale cereale* (SC), *Hordeum vulgare* L. (HV) were used as cover crops. The experiment also included control (C) where no cover crop was used. The experiment was established according to the randomised block design with four replications. The experiment was conducted for two years (2022-2023 and 2023-2024). In both years, the mown cover crops were thoroughly shredded and mixed homogeneously with the soil. Soil samples were taken from 0-20 cm soil depth from each plot 90 days after mowing. The cover crops increased the WAS of the soils and decreased the DR. The WAS of the cover crops were ranked as C < SC < HV < VS+HV < VV+HV < VS < VV. The highest WAS (21.42 %) and lowest DR (52.87 %) were found in VV. The highest increase in SOM was found in VV and VS, while the lowest was found in the control. Significant negative correlations were obtained between WAS and DR (-0.952**) and SOM and DR (-0.938**), while significant positive correlationswere determined between WAS and SOM (0.902**). VV and VS applications of annual legumes are recommended to improve wet aggregate stability and organic matter of soils.

Keywords: Cover crops, dispersion ratio, Nigella Sativa L., organic matter, V. villosa Roth., Vicia sativa L., wet aggregate stability

Introduction

At present, the enhancement of agricultural productivity is predicated upon the expansion and intensification of crop production systems. In the context of developing nations, which often possess constrained resources, the management of soil quality is imperative for the sustenance of ecosystem services. Soil degradation constitutes a pervasive global issue that, in addition to adversely impacting soil conservation, also detrimentally influences agronomic production and economic development, particularly in nations where agriculture plays a pivotal role in economic advancement (Olson et al., 2017). Organic matter deficiency is one of the most important problems in terms of productivity of agricultural soils in Türkiye. Intensive tillage, erosion, monoculture agriculture, chemical fertilisers and pesticides reduce soil organic matter. Therefore,

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cover crops play a vital role in enhancing soil structure and fertility, serving as a sustainable agricultural practice. They improve soil quality through various mechanisms, including erosion reduction, increased organic matter, and nutrient cycling. By incorporating cover crops into agricultural systems, farmers can achieve long-term benefits for soil health and productivity (Demir, 2020a; Demir, 2020b; Demir et al., 2019; Demir and Işık, 2019a; Demir and Işık, 2019b).

Cover crops play a significant role in enhancing soil health and fertility through various mechanisms. They improve soil structure, increase organic matter, facilitate nutrient cycling, and controlling weeds which collectively contribute to sustainable agricultural practices. Cover crops enhance soils by improving structure, increasing organic matter through decomposition, and promoting nutrient cycling. They reduce erosion, boost aggregate stability, enhance water infiltration, and can fix atmospheric nitrogen, ultimately leading to improved soil fertility and agricultural productivity. The decomposition of cover crop residues boosts soil organic matter, contributing to humus formation (MA et al., 2024). While cover crops generally provide numerous benefits for soil health, their effectiveness can be influenced by management practices, environmental conditions, and specific crop types. For instance, grazing cover crops may lead to soil compaction and mixed effects on subsequent crop yields, highlighting the need for careful management (Blanco-Canqui et al., 2023).

The leguminous cover crops (Vicia sativa L., V. villosa Roth. etc.) possess the potential to supply nitrogen via the nitrogen fixation mechanism, while non-leguminous cover crops, including grasses and forbs, may mitigate nitrogen leaching during periods of elevated precipitation (Kuo and Sainju, 1998). Typically, upon the culmination of their growth cycle, cover crops can be integrated into the soil to enhance soil organic matter, thereby facilitating nutrient release through the process of mineralization, or alternatively, they can be transformed into mulches to augment weed management and water conservation, although both outcomes may occur simultaneously (Coppens et al., 2006). The choice and cultivation of a cover crop depends on the most important benefit derived from it and the cultivation system applied. Legumes, cereals or a suitable combination of them are used as cover crops.

Hordeum vulgare L. and Secale cereale commonly known as barley, is effectively utilized as a cover crop due to its numerous agronomic benefits, particularly in weed suppression and soil health improvement. Research indicates that barley cover crops can significantly reduce weed densities and enhance soil properties, making them a valuable component in sustainable agricultural practices. Barley cover crops contribute to improved soil structure and organic matter. They enhance soil aggregate stability and increase total organic carbon levels, which are crucial for maintaining soil health (Liu et al., 2005; Pinnamaneni et al., 2022)

In this study, the effects of different cover crops on wet aggregate stability (WAS), dispersion ratio (DR) and organic matter (SOM) of soil were investigated in the field where Nigella Sativa L. seed was grown at Erciyes University Agricultural Research and Application Centre in Kayseri, Türkiye.

Material and Methods

This experiment was conducted at Erciyes University Agricultural Research and Application Centre (ERÜTAM). The experiment was established according to the randomised block design with four replications. The plots were 4 m wide and 5 m long. The experiment was conducted for two years with 4 replications. Cover crops were planted in 2022 and 2023. In the first year, cover crops were planted on 08.10.2022 and mowing was carried out on 20.05.2023. In the second year, cover crops were sown on 28.10.2023 and mowed on 25.05.2024. The cover crops were mown and mixed with the soil with a disc harrow. In both years, the mown cover crops were thoroughly shredded and mixed homogeneously into the soil. After the mowing process, black cumin sowing was applied in the field. *Vicia sativa* L. (VS), *V. sativa* L. + *Hordeum vulgare* L. (VS+HV), *V. villosa* Roth. (VV), *V. villosa* Roth. + *H. vulgare* L. (VV+HV), *Secale cereale* (SC), *Hordeum vulgare* L. (HV) were used as cover crops (Table 1). The experiment also included control (C) where no cover crop was used. Soil samples were taken from 0-20 cm soil depth from each plot 90 days after mowing. Samples were brought to laboratory in placed bags. Samples were air-dried under room temperature. Samples were sieved through 2 mm sieve and made ready for analyses. Some physical and chemical properties of the soil at the start of the experiment were given in Table 2. Soil analyses revealed that soils (at 0-20 cm) in the experimental field site have a sandy loam (SL) textured soil (74.41% Sand, 15.23% Silt, 10.37% Clay), were slightly alkaline (7.46), and low organic matter (0.89) contents (Soil Survey Staff, 2014).

Soil particle size distribution (sand, silt and clay contents) was analyzed with the use of hydrometer test (Demiralay, 1993). A pressure plate apparatus was used to determine soil moisture at field capacity (FC) and permanent wilting point (PWP) (Hillel, 1982). Available water content (AWC) was then calculated as the difference between FC and PWP (Hillel, 1982). Soil bulk density (BD) was identified as described by Tüzüner

(1990). A wet sieving apparatus was used to determine wet aggregate stability (WAS) (Kemper and Rosenau, 1986). Utilizing the hydrometer method, DR was determined as a structural stability index and it was calculated by Equation 1:

$$DR = (a / b)\ 100 \ldots\ldots (1)$$

Here, while "a" refers to the % of silt+clay that is dispersed from the soil aggregate into suspension, "b" refers to the % of mechanical analyses of silt+clay fractions after the implementation of dispersing agent into the suspension.

Soil pH values were measured with a pH meter and electrical conductivity (EC) values were measured with an EC meter (Richard, 1954). Scheibler calcimeter was used to determine soil lime contents (Soil Survey Staff, 2014). Modified Walkley-Black method was used to determine soil organic matter (SOM) content (Kacar, 1994). Soil available P contents were determined through extraction with 0.5 M NaHCO3 (pH = 8.5) (Olsen et al., 1954). Samples were extracted with NH_4OAc. (pH=7.0) to get soil available potassium contents (Jackson, 1958). Exchangeable cations were determined with ammonia acetate extraction (Kacar 1994). Cation exchange capacity (CEC) values were determined as described by Richard (1954). Micronutrients (Fe, Cu, Mn and Zn) were determined in a spectrophotomer with the use of DTPA extraction (Kacar, 1994). Available calcium and magnesium were determined according to Jackson (1958).

Analysis of variance (ANOVA) was performed to evaluate experimental data using SPSS statistical package (SPSS 19.0, SPSS Inc., 2011). Statistical dissfferences were evaluated using Duncan's multiple range test at 0.01 alpha probability levels. Correlations between the investigated parameters were tested with the use of Pearson's correlation method.

Table 1. Experiment Subjects

No	Treatment	Treatment amount
1	*Vicia sativa* L. (VS)	100 kg ha^{-1}
2	*V. villosa* Roth. (VV)	80 kg ha^{-1}
3	*Hordeum vulgare* L. (HV)	50 kg ha^{-1}
4	*Secale cereale* (SC)	50 kg ha^{-1}
5	*Vicia sativa* L. (VS) + *Hordeum vulgare* L. (HV)	50 kg ha^{-1} + 50 kg ha^{-1}
6	*V. villosa* Roth. (VV) + *Hordeum vulgare* L. (HV)	50 kg ha^{-1} + 50 kg ha^{-1}
7	Control (C)	-

Table 2. Some Physical and Chemical Properties of Soil

Soil properties	0-20 cm	Soil properties	0-20 cm
Clay, %	10.37	Exchangeable Mg, me100g^{-1}	2.65
Sand, %	74.41	Exchangeable Na, me 100 g^{-1}	0.33
Silt, %	15.23	Exchangeable K, me 100 g^{-1}	0.42
Soil texture	SL	Cation exchange capacity, me 100 g^{-1}	10.56
Soil reaction (pH)	7.46	Available Fe, ppm	1.95
Electrical conductivity (EC, ds/m)	0.466	Available Mn, ppm	5.06
Organic matter (OM), %	0.89	Available Cu, ppm	0.95
Total N, %	0.062	Available Zn, ppm	0.77
$CaCO_3$, %	0.46	Bulk density (Db), gr/cm^3	1.57
Available P_2O_5, kg ha^{-1}	95.2	Field capacity (FC), %	17.94
Available K_2O, kg ha^{-1}	973.2	Permanent wilting point (PWP), %	10.31
Exchangeable Ca, me 100 g^{-1}	6.39	Available water content (AWC), %	7.63

Results

The effects of the treatments on wet aggregate stability, dispersion ratio and soil organic matter at 0-20 cm soil depth are given in Figure 1. According to Duncan's multiple comparison test, there was a statistical difference at 1% level between the treatments in terms of wet aggregate stability (WAS), dispersion ratio (DR) and organic matter (SOM) at 0-20 cm soil depth. In the experiment, cover crop treatments increased WAS and SOM values at 0-20 cm soil depth compared to the control. The cover crops increased the WAS and SOM of the soils and decreased the DR in 0-20 cm soil depth. The WAS of the cover crops were ranked as C < SC < HV < VS+HV < VV+HV < VS < VV. The highest WAS (21.42 %) and lowest DR (52.87 %) were found in VV. The highest increase in SOM was found in VV and VS, while the lowest was found in the control. The highest wet aggregate stability at 0-20 cm soil depth was obtained in *V. villosa* Roth. treatment (21.42%), while the lowest was determined in the control treatment (17.07%). There was no statistical difference between *V. villosa* Roth. (VV) and *Vicia sativa* L. (VS) treatments in terms of WAS, DR and SOM. Instead of using wheat cover crops alone, mixed planting with legumes (*V. sativa* L. + *Hordeum vulgare* L. (VS+HV) and *V. villosa* Roth. + *H. vulgare* L. (VV+HV)) was more effective in improving soil structure. Significant negative correlations were obtained between WAS and DR (-0.952**) and SOM and DR (-0.938**), while significant positive correlationswere determined between WAS and SOM (0.902**) (Figure 2).

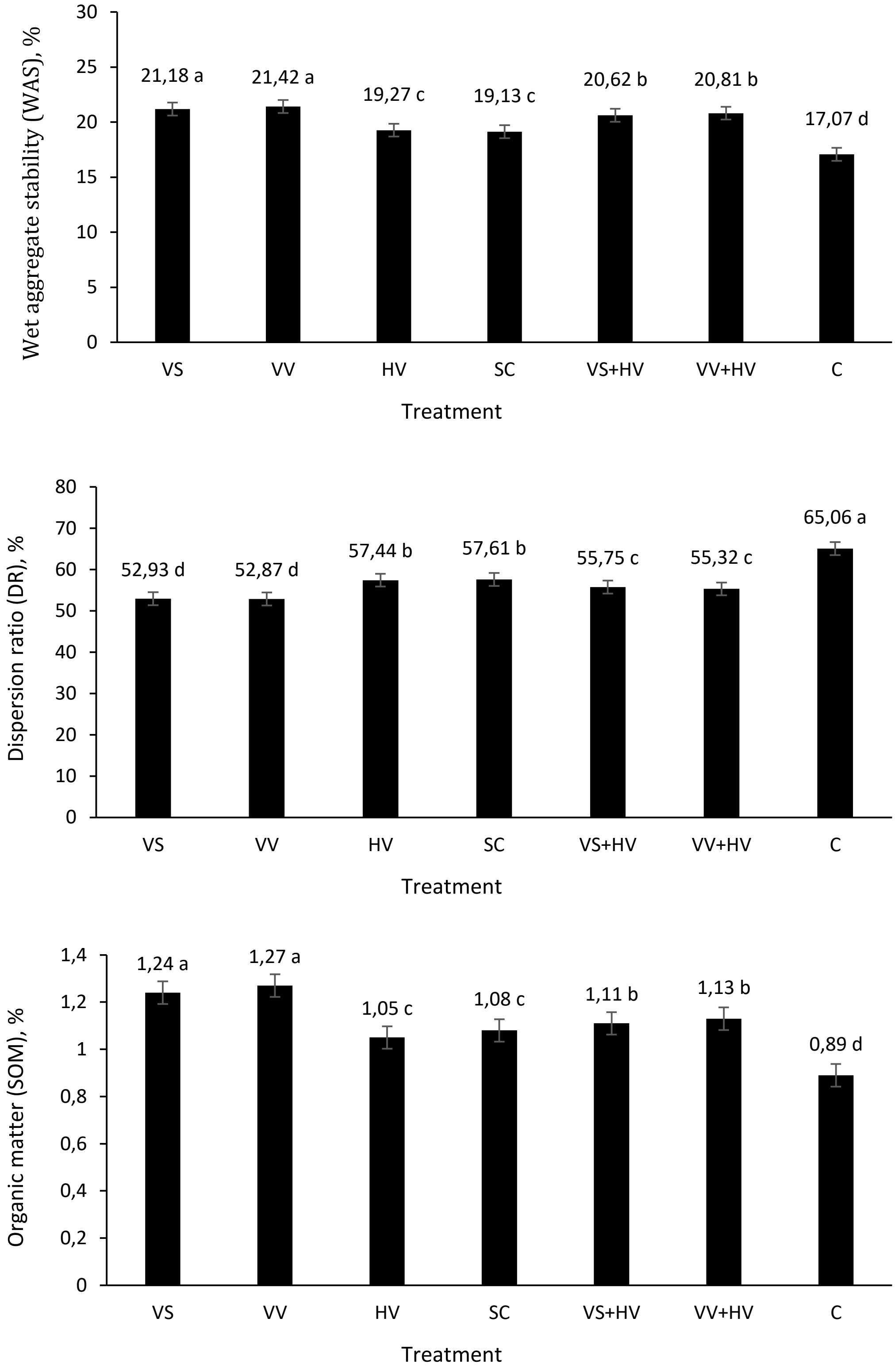

Figure 1. Changes in the Wet Aggregate Stability (WAS), Dispersion Ratio (DR) and Soil Organic Matter (SOM) Amo
Treatments in 0-20 cm soil depth (VS: *Vicia sativa* L., VV: *V. villosa Roth*., HV: *Hordeum vulgare* L., SC: *Secale cereale*,
+HV: *Vicia sativa* L. + *Hordeum vulgare* L., VV + HV: *V. villosa* Roth. + *Hordeum vulgare* L., C: Control), P < 0.01.

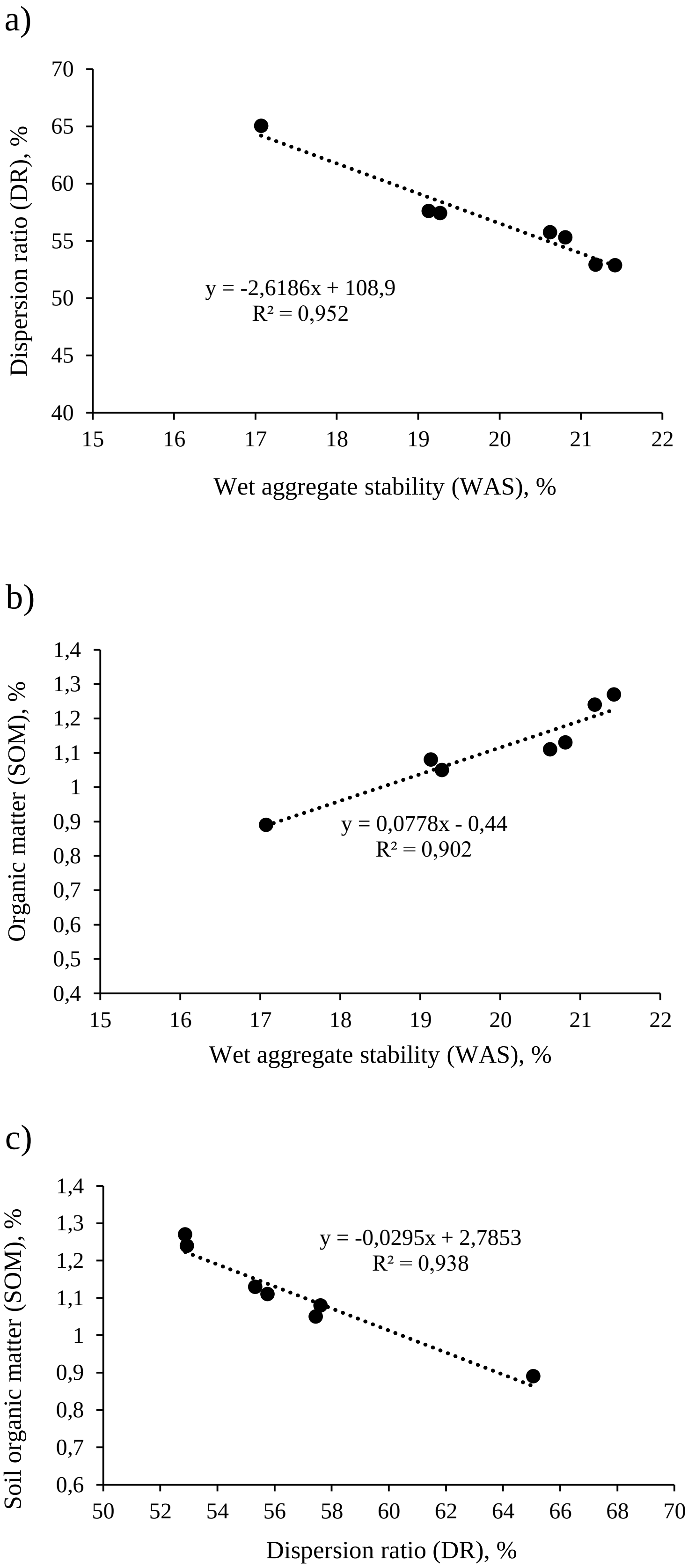

Figure 2. Relationships between WAS and DR (a), SOM and WAS (b), SOM and DR in 0-20 cm soil depths

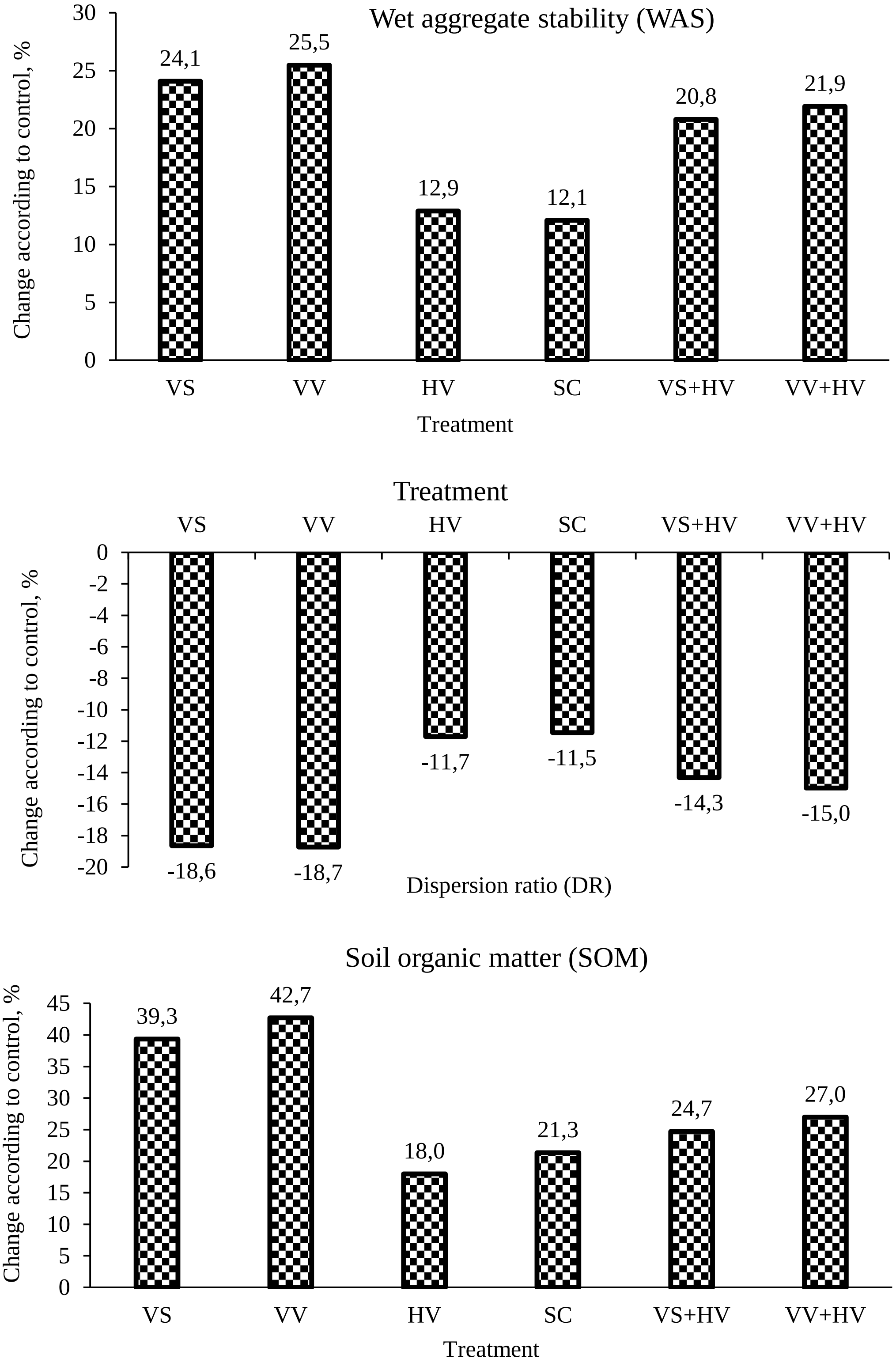

Figure 3. Changes according to control (%) wet aggregate stability (WAS), dispersion ratio (DR) and soil organic matter (SOM) in 0-20 cm soil depths

Discussion

Changes according to control (%) wet aggregate stability (WAS), dispersion ratio (DR) and soil organic matter (SOM) in 0-20 cm soil depths were given figüre 3. The legume cover crops also seem to be more effective than the grains in terms of the improvement of soil structural stability at 0-20 cm soil depths. From these results, it can be concluded that *Vicia villosa* Roth. (VV) and *Vicia sativa* L. (VS) are the most effective cover crops in terms of increasing the aggregate stability and reducing the erosion sensitivity at 0-20 cm soil depths. Our results showed that while the annual *Vicia villosa* Roth. (VV) significantly increased the WAS by 25.5%, it decreased the DR index by 18.7% at the 0-20 cm soil depth. In this study, it was determined that legume, grasses and their mixtures increased the organic matter content of soils between 18.0% and 42.7% (Figure 3). Legume and grasses forage crops not only make the soils they are planted fertile. At the same time, they improve the structure of the soil by increasing the amount of organic matter of the soil with the root and above-ground residues they leave in abundance. Cover crops significantly increase soil aggregate stability, which is crucial for maintaining soil health and preventing erosion. Research shows that cover crops improve soil structure by promoting the formation of stable aggregates through several mechanisms, including reduced soil compaction and increased organic matter content (Demir and Işık, 2020a; Demir and Işık, 2020b). Several winter gramineous species such as rye (*Secale cereal* L.), oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), triticale and ryegrass (*Lolium multiflorum* Lam.) are used as cover crops to maintain or improve soil organic carbon levels (Álvarez et al., 2006). Kaspar et al. (2006) determined that winter cover crops such as oats and rye have the capacity to elevate soil organic carbon in corn-soybean production system. Cover crops contribute to higher organic matter levels, especially in smaller aggregate fractions (<1 mm), which in turn increases aggregate stability (Gentsch et al., 2024). The root systems of cover crops and their associated microbial communities play a vital role in binding soil particles together, thus improving aggregate formation (Demir, 2019; Demir and Işık, 2020a; Demir and Işık, 2020b; Patton et al., 2024). Gülser (2004) reported that to be able to increase the physical properties of the soil and ensure sustainable soil management, integration of bromegrass and alfalfa with the cropping system may be applied. Gülser (2006) reported that cultivation of forage crops increased the aggregate stability of clay textured soil and the highest increase was obtained with bromine cultivation (80.01%) compared to the control (71.76%). Gülser (2006) determined that dispersion ratio (15.30–9.76%) also decreased the compared with the control treatment. In addition, the significant negative correlations among the soil physical properties were obtained between the aggregate stability and dispersion ratio and between mean weight diameter and dispersion ratio. In this study, the dispersion rate also decreased between 11.5 and 18.7 with cover crop applications. Aggregate size distribution and stability in soils is an indicator of soil quality and a decrease in the organic matter level of soils causes a decrease in the stability of aggregates (Six et al., 2000).

Conclusion

The findings of this investigation indicate that varying applications of plant management markedly influence the organic matter dynamics within the soil, as well as the structural properties of the soil across its inherent variations. The legume cover crops also seem to be more effective than the grains in terms of the improvement of soil structural stability at 0-20 cm soil depths. *V. villosa* Roth. (VV) and *Vicia sativa* L. (VS) applications of annual legumes are recommended to improve wet aggregate stability and organic matter of soils. Instead of using wheat cover crops alone, mixed planting with legumes (*V. sativa* L. + *Hordeum vulgare* L. (VS+HV) and *V. villosa* Roth. + *H. vulgare* L. (VV+HV)) was more effective in improving soil structure. It is widely acknowledged that the beneficial impact of cover crops on the physical characteristics of the soil is contingent upon the specific species of plants employed and the prevailing ecological conditions. The use of cover crops improves soil physical properties and soil conservation and consequently improves land productivity and soil health. Consequently, in order to enhance both the quality and productivity of the soil, it is imperative to select cover crops that are specifically suited for this purpose.

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The effect of defuzzification on ET_0 estimation using the Mamdani approach

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Abstract

Accurate estimation of reference evapotranspiration (ET_0) is critical for irrigation planning and water resources management. In this study, ET_0 was estimated using data from 19 meteorological stations in Paraguay and the Mamdani fuzzy inference system, and the effect of defuzzification methods on performance was investigated. The 2018–2020 period was used for training, and the 2021–2022 period for testing; the centroid, bisector, MoM, LoM, and SoM approaches were compared under trapezoidal membership functions. Performance was evaluated using MBE, MAE, RMSE, and R^2. The results showed that the choice of defuzzification was decisive for error and bias. Centroid provided the best fit in both training (RMSE=0.44; R^2=0.83) and testing (RMSE=0.47; R^2=0.80) and produced low bias (MBE training -0.10, testing -0.02). LoM showed the lowest performance (test RMSE=1.74; R^2=0.45) and exhibited a noticeable underestimation bias. The findings indicate that centroid smoothing is the most reliable option for Mamdani-based ET_0 estimation at the Paraguay scale.

Keywords: reference evapotranspiration;Paraguay, Mamdani, Fuzzy logic

Introduction

Evapotranspiration (ET) refers to the total water loss from soil and plant surfaces to the atmosphere and is one of the fundamental components of hydrological cycle and water balance analyses. Reference evapotranspiration (ET_0), the standardized form of this process defined over a reference surface, represents the atmosphere's evaporation demand independently of plant type and agricultural practices (Rahimi Khoob, 2008; Dai et al., 2009; Huo et al., 2012). Reliable estimation of ET_0 plays a direct and decisive role in numerous applications, such as determining agricultural water needs, planning irrigation systems, water resource management, and environmental modeling (Torres et al., 2011; Ferreira and da Cunha, 2020). Although direct measurement methods (e.g., lysimeters) are theoretically possible, they are not feasible in most regions due to high costs and operational limitations (Chia et al., 2020a). The Penman–Monteith (FAO-56 PM) equation, recommended by the FAO as the standard method for ET_0 calculations, is based on meteorological variables such as temperature, humidity, sunshine, and wind speed (Allen et al., 1998). However, the limited number of stations where the necessary meteorological inputs can be measured completely and reliably restricts the applicability of the FAO-56 PM approach on a large scale (Karimaldini et al., 2012). Alternatively developed empirical and semi-empirical methods (e.g., Hargreaves–Samani, Priestley–Taylor) can operate with fewer inputs, but they struggle to provide a universal solution due to their frequent need for region-specific calibration and limited transferability to different climatic conditions (Zhang et al., 2013; Luo et al., 2014).

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This situation has necessitated the investigation of methods that are more flexible, require fewer inputs, and can provide high accuracy in ET_0 estimation.

The limitations of traditional approaches have led to the increasing use of artificial intelligence-based methods, particularly fuzzy logic-based models, in ET_0 estimation (Kisi and Ozturk, 2007; Kumar et al., 2011; Chia et al., 2020). Fuzzy logic approaches stand out due to their ability to represent uncertainties and non-linear relationships in real systems through a rule-based structure and their interpretability.

The limitations of traditional approaches have led to the increasing use of artificial intelligence-based methods and, in particular, fuzzy logic-based models in ET_0 estimation (Kisi and Ozturk, 2007; Kumar et al., 2011; Chia et al., 2020). Fuzzy logic approaches stand out due to their ability to represent uncertainties and non-linear relationships in real systems through a rule-based structure and their interpretability. In this context, the Mamdani-based fuzzy inference system is a classical and explainable approach that reflects expert knowledge in the model using "If–Then" rules, relying on linguistic terms in both the antecedent and consequent parts (Mamdani and Assilian, 1975; Jang et al., 1997; Zadeh, 1999). One of the critical components determining model performance in Mamdani systems is the defuzzification step; because different defuzzification methods can significantly change the error level and systematic bias of outputs despite the same rule base and membership functions (Mendel, 2001; Ross, 2010; Zimmermann, 2001).

A review of the literature reveals that, despite the widespread use of fuzzy logic/ANFIS-based applications in ET_0 estimation, most studies proceed based on a single structure or a single smoothing option. In particular, studies comparing the effects of smoothing methods (such as centroid, bisector, MoM, LoM, SoM) in Mamdani-based systems are limited. In this context, the fact that the defuzzification step is not a "secondary" choice but one of the design parameters that directly determines model performance and bias characteristics should be addressed more systematically in ET_0 applications.

The aim of this study is to estimate ET_0 using a Mamdani-based fuzzy inference system with data obtained from 19 stations in Paraguay and to comparatively evaluate the effect of smoothing methods on model performance. In this context, the 2018–2020 period was defined as the training period, and the 2021–2022 period as the testing period; centroid, bisector, mean of maxima (MoM), largest of maxima (LoM), and smallest of maxima (SoM) smoothing approaches were applied under trapezoidal membership functions. The performance of the models was evaluated using MBE, MAE, RMSE, and R^2 criteria, revealing the practical applicability of the Mamdani approach under data-constrained conditions and the significance of stabilization selection for decision-makers.

Material and Methods

Study Area and Data Sets

Paraguay, located between 19° and 28° south latitude and 54° and 63° west longitude, is situated in the continental desert climate zone. The country covers an area of approximately 448,978 km^2. This study uses long-term meteorological data obtained from 19 stations over a five-year period (2018-2022). Data from 19 meteorological stations obtained from the Paraguay Meteorological Agency were used in this study. The locations of these stations within Paraguay are shown in Figure 1. The geographical coordinates of the stations are given in Table 1.

Paraguay is located between 19° and 28° south latitude and 54° and 63° west longitude and is in the continental desert climate zone. The country covers an area of approximately 448,978 km^2. This study uses long-term meteorological data obtained from 19 stations for the five-year period between 2018 and 2022. The data belong to 19 meteorological stations obtained from the Paraguayan Meteorological Service. The locations of these stations in Paraguay are shown in Figure 1. The geographical coordinates of the stations are given in Table 1. The daily ET_0 value was calculated using the ASCE Penman-Monteith method based on meteorological data such as temperature (T), relative humidity (RH), wind speed (WS), and sunshine duration (SD) obtained from these meteorological stations.

The meteorological data for 19 stations in Paraguay between 2018 and 2022 were considered, with the years 2018-2020 designated as training and 2021-2022 as testing. The input data used in the study were average temperature, average relative humidity, and sunshine duration, while ETo was used as the output. The study was conducted in three different evaluations.

In the study, average temperature, relative humidity, and sunshine duration were selected as inputs for all models, while ETo was selected as the output. The output parameters were selected based on the easiest parameters to obtain. Table 1 provides descriptive statistical values for all 19 stations in Paraguay.

Table 1. Descriptive statistics of the data used in ETo estimation for Paraguay

	Tav.	RH	Rs	ETo
Mean	23.67	70.96	6.99	3.25
Standard Error	0.12	0.23	0.05	0.04
Standard Deviation	3.89	7.90	1.70	1.23
Kurtosis	-0.81	-0.31	0.68	-1.25
Skewness	-0.35	-0.30	-0.40	0.03
Minimum	13.50	45.00	0.00	1.01
Maximum	32.10	93.00	11.70	6.00

When the descriptive statistics for Paraguay and the physical processes in the literature are evaluated together, many studies have indicated that the most decisive variable on ETo is solar radiation (Rs), and that it is the most effective parameter in the outputs used in ETo estimation. According to the FAO 56 PM energy balance equation, the fundamental parameter of ETo is net radiation, which is directly related to Rs. Furthermore, the relative variability (CV) of Rs is the highest in the data, indicating that most of the fluctuations in ETo originate from changes in Rs. Temperature (Ta) is also a secondary important factor; an increase in temperature accelerates evaporation and transpiration processes, thereby increasing ETo. In contrast, the effect of relative humidity (RH) is in the opposite direction, as high humidity reduces the vapor pressure deficit, lowering ETo values. However, in humid climates such as Paraguay, the role of RH is limited, and the effects of Rs and Ta are more prominent. These findings indicate that considering Rs as the primary variable, Ta as the secondary variable, and RH as a complementary variable in modeling studies will yield more accurate results. Since all three parameters are easily measurable and readily available at every station, all inputs were created from Ta, Rs, and RH.

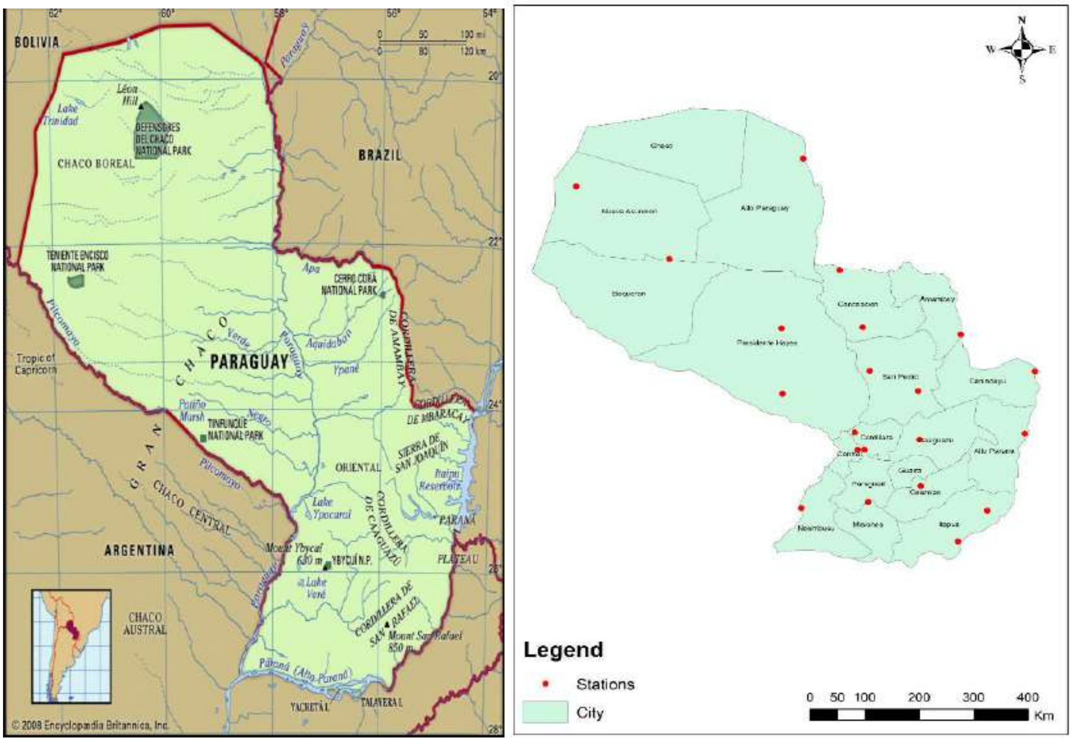

Figure 1. The location of the stations in Paraguay

Mamdani-Based Fuzzy Inference Method

The Mamdani-based fuzzy inference system is a classical fuzzy logic approach first developed by Mamdani and Assilian (1975) to model human expert-based intuitive "If–Then" rules in control problems, which has found widespread use in engineering and environmental sciences (Jang et al., 1997; Zadeh, 1999). In this system, both the antecedent and consequent parts of the rules are defined using linguistic terms and fuzzy sets; in this respect, it differs from the Takagi–Sugeno model, which mostly uses numerical/analytical expressions in the consequent part. The Mamdani approach generally consists of the following steps: fuzzification of inputs using membership functions, evaluation of rules using "and/or" operators (often min–max), combination of rule outputs, and conversion of the final fuzzy output to a numerical value through defuzzification. one of the most common methods of defuzzification is the centroid approach (Mendel, 2001; Ross, 2010). Thanks to its rule structure based on intuitive knowledge and the inclusion of fuzzy expressions in the result section, the

Mamdani model offers significant advantages in terms of interpretability and user-friendly explainability (Zimmermann, 2001).

Model performance evaluation

The precision of the models was evaluated using the coefficient of determination (R2), the mean absolute error (MAE), and the root mean square error (RMSE), (Waller 2003).

Results and Discussion

Considering all 19 stations together, with 2018–2020 as the training period and 2021–2022 as the testing period, the results clearly indicate that the choice of defuzzification in the Mamdani fuzzy inference system (with trapezoidal membership functions) has a pronounced impact on model performance. During training, the Centroid method achieved the best agreement (RMSE = 0.44, R^2 = 0.83), and it largely preserved this skill during testing (RMSE = 0.47, R^2 = 0.80). Moreover, the Centroid method produced MBE values close to zero (training: -0.10; testing: -0.02), demonstrating that it can keep errors low while avoiding systematic bias. This behavior suggests not only a strong fit during training but also a stable generalization capacity when transferred to independent years.

In the overall performance ranking, Bisector followed Centroid. Bisector yielded moderate accuracy with RMSE = 0.54 and R^2 = 0.76 in training, and RMSE = 0.58 and R^2 = 0.72 in testing. However, its consistently negative MBE (training: -0.18; testing: -0.12) indicates a tendency toward systematic underestimation. From an application perspective, such bias is important because underestimating ET_0 may lead to under-allocation of irrigation demand or underestimated water requirements in water balance studies, thereby potentially influencing management decisions.

The remaining methods showed weaker outcomes in terms of both error magnitude and bias structure. The MoM method performed below Bisector, with RMSE = 0.84 and R^2 = 0.67 during training and RMSE = 0.87 and R^2 = 0.62 during testing, alongside consistently negative MBE (training: -0.33; testing: -0.28). The SoM method exhibited a comparable level of explained variance to MoM (testing R^2 = 0.61), but it clearly differed in bias direction, producing positive MBE values (training: 0.70; testing: 0.75) that indicate systematic overestimation. Such behavior may be particularly problematic under hot and dry conditions, where overestimated ET_0 can translate into inflated irrigation requirements and increased operational risk. The poorest performance was obtained with LoM, where errors were substantially higher and explained variance notably lower (training: RMSE = 1.72, R^2 = 0.51; testing: RMSE = 1.74, R^2 = 0.45). The strongly negative MBE values (training: -1.35; testing: -1.30) further confirm a pronounced tendency toward severe underestimation.

Overall, these findings highlight that the defuzzification stage is a critical component shaping the behavior of Mamdani-based ET_0 estimates. The superiority of the Centroid method can plausibly be attributed to its ability to represent the aggregated output membership distribution using its “center of area,” which helps balance the influence of extremes and thus reduces both error and systematic bias. In contrast, methods such as LoM, MoM, and SoM—by emphasizing specific points of the aggregated membership function—can shift predictions downward (LoM/MoM) or upward (SoM), especially in a setting where all stations are pooled and spatial climatic variability is substantial. Therefore, method selection should not rely solely on RMSE and R^2, but should also explicitly consider the sign and magnitude of MBE to control systematic under- or over-estimation.

Finally, because Table 3 reports the aggregate performance across all stations, it effectively summarizes the overall skill but may mask station-to-station variability and localized performance drops. To strengthen interpretation and support operational adoption, further analyses are recommended, including station-level error distributions, seasonal/monthly performance assessments, and a dedicated evaluation of bias under high-ET_0 conditions (e.g., warm–low humidity periods). Within this framework, the current results clearly indicate that Centroid defuzzification provides the most reliable and balanced option for Mamdani-based ET_0 estimation at the scale of Paraguay.

Table 3. Statistical performance criteria for ET_0 estimation in Paraguay using the Mamdani approach for the training (2018–2020) and testing (2021–2022) periods.

	Training				Testing			
	MBE	MAE	RMSE	R2	MBE	MAE	RMSE	R2
Centroid	-0.10	0.35	0.44	0.83	-0.02	0.37	0.47	0.80
Bisector	-0.18	0.40	0.54	0.76	-0.12	0.43	0.58	0.72
Mom	-0.33	0.68	0.84	0.67	-0.28	0.68	0.87	0.62
Lom	-1.35	1.51	1.72	0.51	-1.30	1.49	1.74	0.45
Som	0.70	0.86	1.11	0.63	0.75	0.89	1.14	0.61

Conclusion

This study evaluated the impact of different defuzzification strategies on ET_0 estimation using a Mamdani fuzzy inference system (with trapezoidal membership functions) based on data from 19 meteorological stations in Paraguay, with 2018–2020 used for training and 2021–2022 for testing. The results clearly demonstrate that defuzzification is a key design choice that significantly influences both predictive accuracy and bias characteristics.

Across all performance metrics, the Centroid method emerged as the most accurate and balanced option. It maintained high agreement in both training (R^2 = 0.83, RMSE = 0.44) and testing (R^2 = 0.80, RMSE = 0.47) while producing MBE values close to zero (training -0.10, testing -0.02), indicating minimal systematic bias. Although Bisector ranked second, it yielded higher errors and lower explained variance than Centroid and showed a consistent underestimation tendency. MoM and particularly LoM exhibited weak performance due to larger errors and pronounced negative bias, whereas SoM produced positive bias, implying systematic overestimation that may be risky for irrigation and water management applications.

Overall, the findings indicate that Centroid defuzzification is the most suitable choice for Mamdani-based ET_0 estimation at the scale of Paraguay, and that defuzzification should be treated as an explicit model-design decision rather than a default step. Future work should reinforce these conclusions through station-level mapping of performance, seasonal bias analysis, and targeted evaluation under high-ET_0 conditions, where systematic under- or overestimation may have the greatest practical implications.

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Estimation of soil temperature at different depths of soil profile

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Abstract

Prediction of soil temperature is one of the most important components in sustainable crop production. Heat diffusivity is known factor to predict soil temperature. The aim of this study is to determine soil temperatures from soil surface to 50 cm soil depth using the heat diffusivity coefficient values obtained from the functional relationship using measured meteorological data. Heat diffusivity values were estimated for 5, 10, 20 and 50 cm soil depths according to mean daily soil temperature values of Meteorology Station between May – July 2012, and heat diffusivity values for these soil layers were predicted using a parabolic function. Root Mean Square Error values between soil temperature estimated from the meteorological data and from the function for 5, 10, 20 and 50 cm soil depths were determined as 0.054, 0.093, 0.099 and 0.012, respectively. As a conclusion, daily soil temperature changes can be estimated for non-measured soil temperatures in different soil depth using the heat diffusivity values estimated from the parabolic functions.

Keywords: Soil depth, temperature, heat diffusivity, estimation, parabolic function.

Introduction

In the theoretical investigation of soil temperature, the thermal diffusivity coefficient is important in controlling the soil thermal regime. Soil temperature varies along with thermal diffusivity along the soil profile, depending on soil structure, climatic conditions, vegetation, etc. The functional relationship between the thermal diffusivity coefficient, thermal conductivity, and soil heat capacity is essential for modeling and predicting soil temperature.

Heat transport processes in porous media are driven by thermal properties such as thermal conductivity, heat capacity, and thermal diffusivity. In models designed to predict heat transport, thermal diffusivity is considered a fundamental parameter, along with physical properties such as the medium's mineralogical composition, bulk density, and water content (de Vries, 1963; Kasubuchi, 1984; Cote and Konard, 2005; Lu et al., 2007). In a study by Saito et al. (2014), prediction models for thermal conductivity and thermal diffusivity were developed appropriate to regional conditions. Huang et al. (2014) used soil temperature measurements at two different depths to investigate the thermal field of the soil. The change in thermal diffusivity in the lower layers of the soil is not significant. In a study conducted by Zhang et al. (2014) using 337 soil samples taken from 11 different points, it was shown that the thermal diffusivity coefficient at a depth of 150 m was between 1.270 and 1.804.10-6 m2/sec-1, and at a depth of 110 m was between 0.915 and 1.801.10-6 m2sec-1. Zambra and Moraga (2013), in applying the mathematical model expressing two-dimensional energy and mass diffusion, determined that the thermal diffusivity coefficients in wet and dry sand-containing soils were 4.944.10-7 m2/sec-1and 2.022.10-7 m2/sec-1, respectively. Thermal properties of soil, such as thermal conductivity, thermal diffusivity, and heat capacity, are also important in the theoretical and practical investigation of temperature distribution, the depth and lag time of heat decay along the soil profile, and one-

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and two-dimensional heat transport (Chung and Horton, 1987; Ekberli et al., 2015a,b; Ekberli and Sarılar, 2015b; Sesveren et al., 2015). The aim of this study is to estimate daily soil temperature changes at different depths of the 0-50 cm soil layer based on thermal diffusivity coefficient values obtained from meteorological data according to functional relationships.

Material and Methods

The data used in this study were obtained from 92 days between May 1, 2012, and July 31, 2012, at the Bafra Meteorological Station in Samsun province. Daily soil temperature values at 5, 10, 20, and 50 cm soil depth were used as the study material. In determining the distribution of heat waves along the soil profile, the basic heat transport equation

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} \quad \left(0 \le x < \infty,\ t > -\infty\right) \tag{1}$$

and the solution obtained according to the boundary condition including the phase change between the temperature changes at the soil surface and depth, expressed by the function

$$T(x,t) = T_0 + Ae^{-\sqrt{\frac{\omega}{2a}}x}\cos\left(\sqrt{\frac{\omega}{2a}}x - \omega t\right) \tag{2}$$

(where - soil surface mean temperature, ºC; A- amplitude, ºC; $\omega = 2\pi / P$ - angular frequency, sec^{-1}; a - thermal diffusivity coefficient, m^{2}sec^{-1}; x- soil depth, cm; t- time, sec; P - period) were used (Nerpin and Chudnovski, 1984; Monteith and Unsworth, 1990; Hillel, 1998; Cichota et al., 2004; Gülser and Ekberli, 2004; Ekberli, 2006; Gao et al., 2007; Lei et al., 2011; Evett et al., 2012; Arkhangelskaya, 2014; Arias-Penas et al., 2015; Hu et al., 2016; Badache et al., 2016).

The thermal diffusivity coefficient in the soil layer was calculated using meteorological data according to the expression

$$a = \frac{\omega\left(x_i - x_{i+1}\right)^2}{2\left(\ln(A_i / A_{i+1})\right)^2} \quad \left(i = \overline{1,n}\right) \tag{3}$$

(where A_i and A_{i+1} are the temperature amplitude of the soil at x_i and x_{i+1} depths, ºC;) (Nerpin and Chudnovski, 1984; Gülser and Ekberli, 2004; Ekberli, 2006; Trombotto and Borzotta, 2009; Correia et al., 2012; Ekberli and Sarılar, 2015a; Arias-Penas et al., 2015). The average thermal diffusivity was calculated based on values obtained between May and July 2012.

A parabolic relationship $\left(a(x) = bx^2 + cx + d\right)$ was used to determine the functional expressions between soil thermal diffusivity and depth.

The root mean square error (RMSE) between soil temperature values calculated from meteorological data and functions was calculated using the following equation:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - y_i')^2\right]^{1/2} \tag{4}$$

Where and are the measured and calculated temperature values, respectively.

Results and Discussion

Average daily temperature values at soil depths of 5, 10, 20, and 50 cm for 92 days between May 1, 2012, and July 31, 2012, at the Bafra Meteorological Station in Samsun province are given in Table 1.

Table 1. Temperature (ºC) values at different soil depths (01.05-31.07.2012)

Depth, cm	Minimum	Maximum	Mean	Std. Dev.	Var. Coef. %
5	18.1	33.4	24.77	4.09	16.51
10	18.5	31.5	24.10	3.68	15.32
20	18.1	29.8	23.88	3.48	14.84
50	16.2	25.5	21.93	3.13	14.42

During the research period, the lowest soil temperature (16.2ºC) was measured at 50 cm and the highest (33.4ºC) at 5 cm at four different soil depths. The highest average soil temperature (24.77ºC) was measured at 5 cm, and the lowest average soil temperature (21.93ºC) was measured at 50 cm. It is observed that the average temperature decreases as one descends from the soil surface to deeper layers.

The standard deviation and coefficient of variation values for soil temperature were found to decrease as one descends to lower layers. The standard deviation and coefficient of variation values for soil temperature were found to be highest at 5 cm soil depth (4.09ºC and 16.51%, respectively) and lowest at 50 cm soil depth (3.13ºC and 14.42%, respectively). This indicates that daily temperature variation decreases as one descends to lower layers.

In examining the temperature change in soil and the estimation of the solution of the heat transport equation, thermal diffusivity is generally assumed to be constant over time (Arkhangelskaya, 2014; Arias-Penas et al., 2015; Ekberli and Sarılar, 2015a). As one descends into the lower soil layers, the physical properties of the soil change and significantly affect the change in thermal diffusivity. Therefore, soil depths must be taken into account in the evaluation of thermal diffusivity. Thermal diffusivity initially reaches maximum values in soil horizons other than the plow layer, with a rapid increase (very close to linear) when the moisture content is at field capacity, and reaches lower values at the saturation point. It is known that thermal diffusivity decreases with decreasing soil moisture content (Şapovalov, 1962; Kurtener and Çudnovski, 1979; Voronin, 1986; Özdemir, 1998; Ekberli et al., 2005c). The variation in thermal diffusivity with soil depth can be expressed using a parabolic relationship. Thermal diffusivity increases rapidly toward a depth of 50 cm, then decreases and reaches a near-constant state. Therefore, the relationships between soil depth (0.05-0.50 m) and the thermal diffusivity coefficient are determined using the parabolic (5) function as follows:

$$a(x)\cdot 10^6 = -35.269\,x^2 + 48.013\,x + 0.489 \quad (R^2 = 0.99) \tag{5}$$

Parabolically calculated average soil temperature (T) and amplitude (A) values for the 15, 30 and 40 cm soil layers, where no meteorological measurements were made, as well as the thermal diffusivity coefficients (h) calculated according to the function (5) in these layers, are given in Table 2. The lowest thermal diffusivity (2.80 10-6 $m^2 sec^{-1}$) was determined in the 5 cm soil layer. In general, thermal diffusivity is higher between the 20 and 50 cm soil layers, and an increasing trend in thermal diffusivity values is observed as one descends from the soil surface to the lower layers.

Table 2. Average temperature (T), amplitude (A) and thermal diffusivity (a) values for different soil depths.

Soil depth, cm	T, °C	A, °C	a, $m^2\,sec^{-1}$
5	24.77	2.90	$2.80\cdot10^{-6}$
10	24.10	2.50	$7.27\cdot10^{-6}$
15	24.06	2.15	$6.90\cdot10^{-6}$
20	23.88	2.00	$8.68\cdot10^{-6}$
30	23.18	1.70	$11.72\cdot10^{-6}$
40	22.57	1.40	$14.05\cdot10^{-6}$
50	21.93	1.10	$15.68\cdot10^{-6}$

Using the thermal diffusivity values obtained from function (5), the daily average hourly soil temperature values calculated for the 5, 10, 20, and 50 cm layers calculated according to solution (2) are given in Figure 1. The average relative error between the experimental (meteorological) thermal diffusivity values (a_d) and the values calculated with the parabolic function (5) (a_h) was found to be 7.79%. The RMSE between the meteorological data and the soil temperature values calculated with the parabolic function was found to be 0.054, 0.093, 0.099, and 0.012 for the 5, 10, 20, and 50 cm soil layers, respectively.

In addition to the average temperature and amplitude values determined by the parabolic function for the 15, 30 and 40 cm layers where no meteorological measurements were made, the hourly average temperature values calculated according to solution (2) using the values obtained according to the thermal diffusivity function (5) are shown in Figure 2.

Soil thermal diffusivity coefficients determined using the parabolic function yielded low relative error compared to experimental data, and average soil temperature values calculated using the determined thermal diffusivity coefficients yielded results very close to meteorological values. This suggests that it is possible to theoretically determine soil temperature values by calculating average soil temperature, amplitude, and thermal diffusivity coefficients using the parabolic function in unmeasured layers.

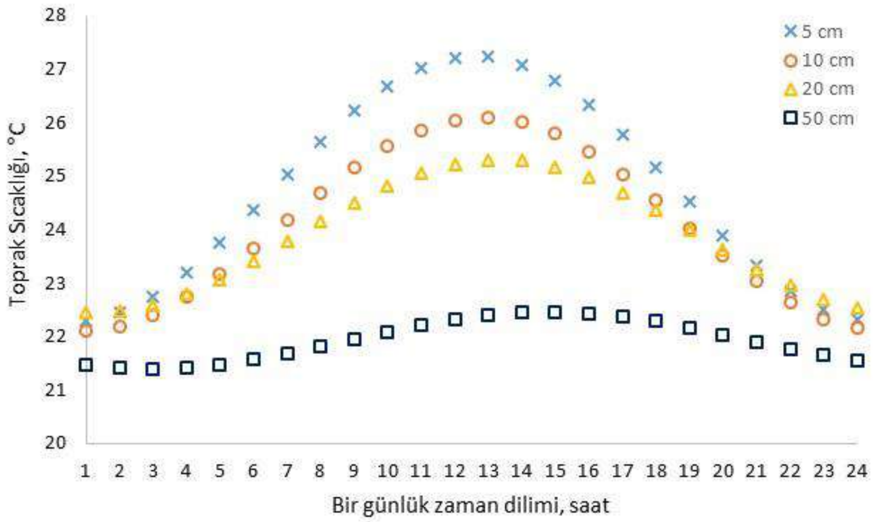

Figure 1. Daily temperature changes at meteorologically measured soil depths.

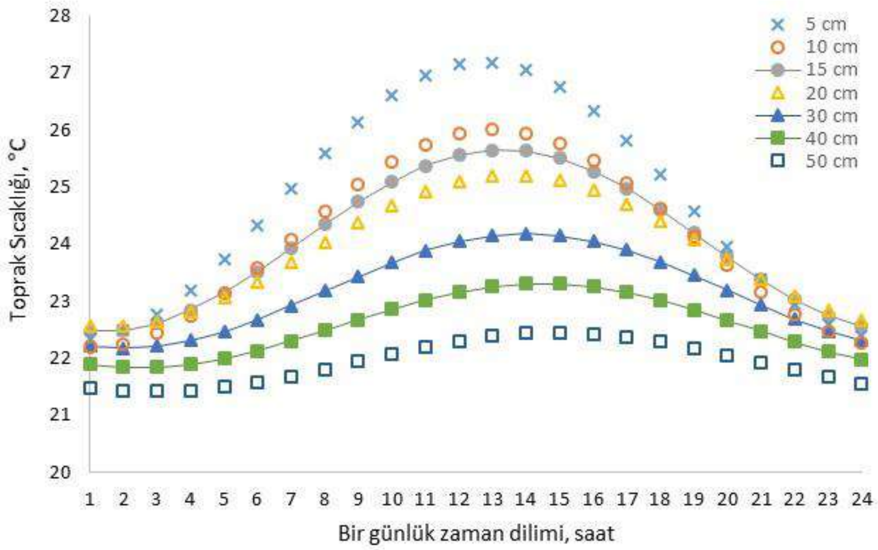

Figure 2. Daily temperature changes at depths with and without meteorological measurements.

Conclusion

The average temperature and amplitude in soil layers are the thermal parameters necessary to determine thermal diffusivity and temperature change. The thermal diffusivity coefficient obtained by using the parabolic function to theoretically express soil temperature was found to be very close to the values obtained from experimental data for different soil layers and yielded the lowest relative error. It appears possible to use parabolic relations to calculate the average temperature amplitude and thermal diffusivity required to apply the heat transport equation to estimate temperature changes in unmeasured intermediate soil layers.

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The Parametric Evaluation Approach for Productivity Index

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Abstract

The primary goal of this study was to use a parametric approach known as the productivity index model to ascertain the crop productivity of the soils at the Field Plants Central Research Institute-Ikizce Research Farm, which is situated south of Ankara. Crop productivity is estimated by the soil productivity model, which takes into account the properties of the soil that influence root development. A thorough soil map scaled to 1/5000 was used to determine the texture, structure, depth, pH, coarse fragment, bulk density, and organic matter of the research area. A productivity index (PI) map was created following the analysis and evaluation of soil characteristics using geographic information system techniques. Furthermore, the use of Geography Information System (GIS) methodologies is crucial for mapping the study and estimating the productivity index.

Keywords: Productivity Index, Soil Characteristics, GIS.

Introduction

Unconscious and unplanned land use and intense pressure on land; rapid soil erosion, resulting in excessive surface runoff and subsequent floods and inundations, the accumulation of eroded soil in valuable agricultural lands, settlements, dams, and ports, soil erosion on slopes and the gradual reduction of soil thickness leading to the exposure of bedrock and the loss of the land's water retention and storage capacity, pollution resulting from excessive fertilization without considering soil and plant characteristics, the formation of arid areas due to uninformed irrigation, loss of growing environments, increased rural poverty, intensified migration from rural areas to cities, and many other ecological, social, economic, and cultural problems are being experienced. This situation leads to the degradation of natural resources and thus jeopardizes sustainable development. Preventing such negative outcomes is possible by clearly defining the current operational areas of sectors such as forestry, agriculture, pasture, settlement, industry, transportation, etc., which utilize land, based on biophysical, social, economic, cultural, and environmental variables, and ensuring that lands and soils are used in accordance with their quality and characteristic features.

Özden et al. (2001) conducted a study on the applicability of the productivity index model in some soil orders in the Ankara region, using soil parameters such as available water, bulk density, soil reaction, electrical conductivity, and root development in the model. They determined the PI values of the soils as Aridisol, Inceptisol, and Entisol in descending order. Additionally, Dengiz and Özcan (2006) conducted a study to determine the productivity status of Samsun-Bafra soils using a geographic information system (GIS). After calculating the PI values using the square root formula, the PI classes of each mapping unit were determined. According to the results obtained, the total area of the study area is 79,255.2 ha. Of this, 7% (5,547.8 ha) consists of water surfaces, coastal dunes, and settlements, while 62.4% (5,028.0 ha) of the land is highly productive and productive (I and II) in terms of productivity, 9.0% (7,216.9 ha) is classified as moderate (III), 12.5% (1,010.5 ha) is classified as unproductive (IV) in terms of agricultural use, and 9.1% (7,368.6 ha) is classified as highly unproductive. In addition, the productivity parameters that hinder agricultural use of the

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soils were determined, and their distributions were shown on maps. Furthermore, a soil database for the study area was created using a GIS system.

This study aims to determine the productivity characteristics of the soils at the İkizce Research Farm of the Field Crops Research Institute using a parametric approach known as the productivity index model.

Material and Methods

Study area

The study was conducted at the Field Crops Research Institute, İkizce Research Farm. The study area is located between the 45th km of the Ankara-Haymana Highway and the coordinates 4383259N-470201E, 4383259N-470400E, 4383426N-470400E, and 4383426N-470201E (WGS84, Zone 36, UTM m) coordinates. The study area, which is approximately 534.4 ha, has an elevation of 1055 m above sea level. The annual average temperature is 11.8 °C and the annual average precipitation is 410.5 mm (DMI, 2003). The study area, which has very different topographic features (flat, slope, hill, etc.), is predominantly flat and undulating. Five different soil series (Cayırlı, Meteroloji, Nizamiye, Gölet, and İkizce) are found in the study area (Dengiz, 1998). With an area of 1,231.2 ha, the Meteroloji series covers the largest area within the study area. The study area is primarily used for irrigated agriculture but also includes forested and pasture areas.

The soil properties considered in the study were taken from a detailed 1:5,000 scale soil map previously prepared by Dengiz (1998). The ArcGIS GIS program was used to analyze the data.

Method

The productivity index model, a parametric approach to determining the productivity characteristics of soils, is a model that calculates the productivity value of soil by taking into account certain soil characteristics that affect plant root development.

The main principle behind the productivity index model developed by Delgado (2003) is that optimal conditions must exist in the plant's root zone to ensure the best possible plant growth in the soil. The soil productivity index is calculated using the following formula, as shown in Figure 2.

$$\text{Productivity index (PI)} = \sum_{i=1}^{n} (Ai.Bi.Ci.Ki)$$

Factors given in the formula;

Factor A: Air-water relationship status at horizon i

- Arid climate (P/ETP < 0.5); Factor A = Sub-factor A1
- Temperate climate (P/ETP > 2.0); Factor A = Sub-factor A2
- Between semi-temperate and arid climate (0.5 < P/ETP < 2.0); Factor A = The most limiting value (smallest numerical value) between sub-factors A1 and A2

P = precipitation, ETP = Potential evapotranspiration

Factor B: Conditions that inhibit the development of plant roots in the i horizon

- If the amount of coarse particles (skeletal fraction) in the soil is equal to or less than 30%, Factor B = Subfactor B1
- If the amount of coarse particles (skeletal fraction) in the soil is greater than 30%, Factor B = Subfactor B2

Factor C: Potential productivity status of the i horizon

- Temperate climate (P/ETP > 2.0); Factor C = Subfactor C1
- Arid climate (P/ETP < 0.5); Factor C = Subfactor C2
- Between temperate and arid climate (0.5 < P/ETP < 2.0); Factor C = The most limiting value (smallest numerical value) between sub-factors C1 and C2

Factor K: Weighting factor based on the thickness of each horizon within the soil profile

PI takes values between 0.00 and 1.00. If a certain level of soil characteristics in the root zone does not limit plant root development, the PI value is 1.00; however, if this characteristic makes plant root development impossible, the PI value is 0.00. Values between 1.00 and 0.00 vary according to the degree to which the soil characteristic limits root development (Table 1).

Table 1. Productivity index values and suitability classes

PI	Class
>0.50	1- Very high
0.30-0.50	2- High
0.10-0.30	3- Moderate
<0.10	4-Low

Results and Discussion

The total area of the study area is 5343.5 da, of which 4716.6 da is used for agricultural activities, while 626.9 da consists of farm buildings, roads, marshes, ponds, and rocky areas. When evaluated based on the productivity index (PI), 3,312.8 da (70.2%) of the study area falls into the high and very high categories, 806.8 da (17.1%) into the medium category, and the remaining 596.7 da into the low PI category (Figures 2). The Çayırlı series of lands, which covers a total area of 989.3 da, consists mostly (849.9 da) of lands with very high suitability according to the PI classification. The remaining area consists of lands with agricultural potential and a high suitability classification. The Meteoroloji series, covering an area of 1,231.2 da, includes the M2.D3t2d2 mapping unit (54.1 da), which has steep slopes and shallow soil depth, and thus consists of lands with medium suitability according to the PI classification (Table 3). The Nizamiye Series soils, which cover an area of 523.5 da, are very heavy in texture, with drainage issues in some areas, leading to the formation of air pockets in the plant root zone, thereby falling into the medium suitability class. All soils belonging to the İkizce Series (1146.4 da) form high and very high suitability classes, similar to the Çayırlı Series.

Table 2. PI values and PI classes for each land mapping unite in the study area soil series

Series	PI value	PI class	Area (da)	Ratio (%)
Çayırlı				
Ç2.B1id4	0,75	1	579,9	12,3
Ç2.C2t2d2	0.41	2	120,1	2,5
Ç2.C2t3K1d1	0.34	2	19,3	0,4
Ç2.A1it1d4	0.75	1	38,3	0,8
Ç2.B1t1d3	0.68	1	231,7	4,9
Meteroloji				
M2.D3t2d2	0.28	3	54,1	1,1
M2.B1it1d3	0.48	2	987,5	20,9
M2.C2t1d3	0.48	2	189,6	4,0
Nizamiye				
N3.A1FYd4	0.27	3	523,5	11,1
İkizce				
Iz3.B2it1d4	0.55	1	578,1	12,2
Iz3.C3t2d3	0.31	2	440,7	9,3
Iz3.B1yt1d4	0.55	1	127,6	2,7
Gölet				
G1.C3t2d2	0.13	3	61,6	1,3
G1.E3t2d1	0.06	4	56,6	1,2
G1.B2t2d2	0.13	3	177,6	3,8
G1.E3t3K2d1	0.06	4	361.7	7,7
G1.B2t3K2d1	0.06	4	178,4	3,8

Soil depth, structure, and clay content are important parameters that affect the water holding capacity of soils. Benny and Stephens (1985) note that soil depth is an effective factor in determining soil quality, particularly in terms of nutrient elements and the amount of water available to plants. Similarly, Rezaei and Gilkes (2005) emphasize that the physical properties of soil are particularly important for pasture areas where fertilization is not possible. Finally, in the Gölet series, the majority of soils in this series have a high variety and degree of limitation of factors that are unfavorable for plant root development (very shallow, high internal rock content, coarse texture, low water-holding capacity, etc.), making them unsuitable for agricultural use.

In a similar study, Dengiz (2007) used a geographic information system to determine the productivity and erosion status of soils in the Çatalkaya basin in Ankara with the help of a model. The model takes into account certain physical and chemical parameters that affect the plant root system in determining soil productivity, while considering soil, terrain, and climate parameters in determining erosion status. According to the results of the study, 75.9% of the area was found to have high and very high productivity characteristics, while 30.3% was found to be at high and very high erosion risk. Additionally, a land classification system was created based on the model productivity index (PI) and erosion risk, and some measures and recommendations were made for sustainable land use planning.

Figure 2. PI class map for the study area

When comparing the results of this method with those of a previous land evaluation study conducted in the region using a computer program (Yüksel and Dengiz, 2001) (Şenol and Tekeş, 1995), it was observed that the results were consistent with each other. In the land evaluation conducted using the ILSEN software package, the prime agricultural lands and very good agricultural lands classified as Class 1 and Class 2 in terms of suitability for agricultural use accounted for 64.3% of the total area, while the very high and high suitability classes accounted for 70.2% of the area according to the PI suitability classification. Additionally, in terms of non-agricultural areas, the land evaluation study shows that lands unsuitable for agricultural use account for 11.5% of the total area, while the PI classification indicates that low-suitability areas account for 12.7% of the total area.

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Evaluation of soil structural parameters with VESS scores

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Abstract

Soil water and air movement, water retention and aeration capacity, plant nutrient availability, plant root development, macro and microorganism activity are related to soil structure. Appropriate soil structure and high aggregate stability are very important in terms of plant production, sustainable soil management and erosion resistance. In this study, the relationships between the visual soil structure evaluation method (Visual Evaluation of Soil Structure-VESS), which can be easily determined in the field, and the erosion susceptibility parameters obtained because of laboratory analysis were revealed. VESS scores of the soil were determined for 50 sampling points representing 0-30 cm depth taken from different fields and land uses. In laboratory conditions, the textural fractions (sand, silt, clay), wet aggregate stability, structure stability index, dispersion ratio, clay ratio, mean weight diameter (MDW) contents of the soils related to structure were determined. A positive statistically significant correlation was determined between VESS scores and clay, aggregate stability. Negative correlations were determined between VESS and MDW, sand. As a result of the study, it was suggested that VESS scores can be easily determined in the field, the physical quality of the soil can be evaluated, and action plans can be created in advance for possible risk situations.

Keywords: Visual evaluation, erosion, physical quality

Introduction

Environmental problems such as global warming, erosion, incorrect and inappropriate land use accelerate soil loss, seriously threatening agricultural production and ecosystem balance. Soil is not only a medium for plant roots; it is also a critical life resource for water retention, nutrient cycling, and the preservation of biodiversity. Therefore, protecting and assessing soil structure is crucial for sustainable agriculture and environmental management. Soil structure is one of the most important indicators of soil physical quality. Disruptions in structure directly impact both agricultural yields and ecosystem services (Surface crusting, Soil compaction, Aggregate instability, Erosion, Layering (plate formation), Salinization and sodification, Water permeability and aeration problems When soil structure is disrupted, water, air, root growth, and microbial life are directly compromised, creating serious risks to agricultural yields and sustainability. Soil structure has a significant impact on parameters such as water retention and movement in the soil, erosion, nutrient cycling, root development, and crop yield (Bronick and Lal, 2005). In order to reveal the susceptibility of soil to erosion, the relationships between the parameters causing erosion and soil properties need to be evaluated (Celilov and Dengiz, 2019).

The Visual Evaluation of Soil Structure (VESS) scoring system, one of the methods used to assess soil physical structure, provides a quick, practical, and visual assessment of soil quality, providing a guiding tool for taking measures against these problems (Ball et al., 2007; Guimarães et al., 2011) . Soil water and air movement,

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water retention and aeration capacity, plant nutrient availability, plant root development, macro and microorganism activity are related to soil structure. VESS aims to provide farmers, consultants, and researchers with an easily applicable method based on visual observation. During the evaluation, criteria such as aggregate size, ease of separation, root density, and pore status are taken into account. Peerlkamp (1959) pioneered visual soil structure assessments, Ball et al. (2007) modernized this approach, and Guimarães et al. (2011) standardized it by adapting it to tropical conditions.

In recent years, phone applications have become available that allow farmers to easily use VESS scores by photographing soil samples. We defined the VESS score in the card and then defined it in the application with the photo, and it gave similar results. VESS score definition becomes easier this way. However, this method is not widely used. There is only one study (Çelik et al.2020) in Türkiye, but they evaluated soils under different soil management in a single field. It is not known how this applies to different soils and land uses. In addition, visual soil and structure assessment methods significantly contribute to farmers' understanding and perception of soil quality (Mueller et al., 2009).

This study aimed to evaluate VESS scores across different land uses in a semiarid climate region (Isparta-Central District) and to assess the relationships between some soil properties,structural parameters and VESS scores.

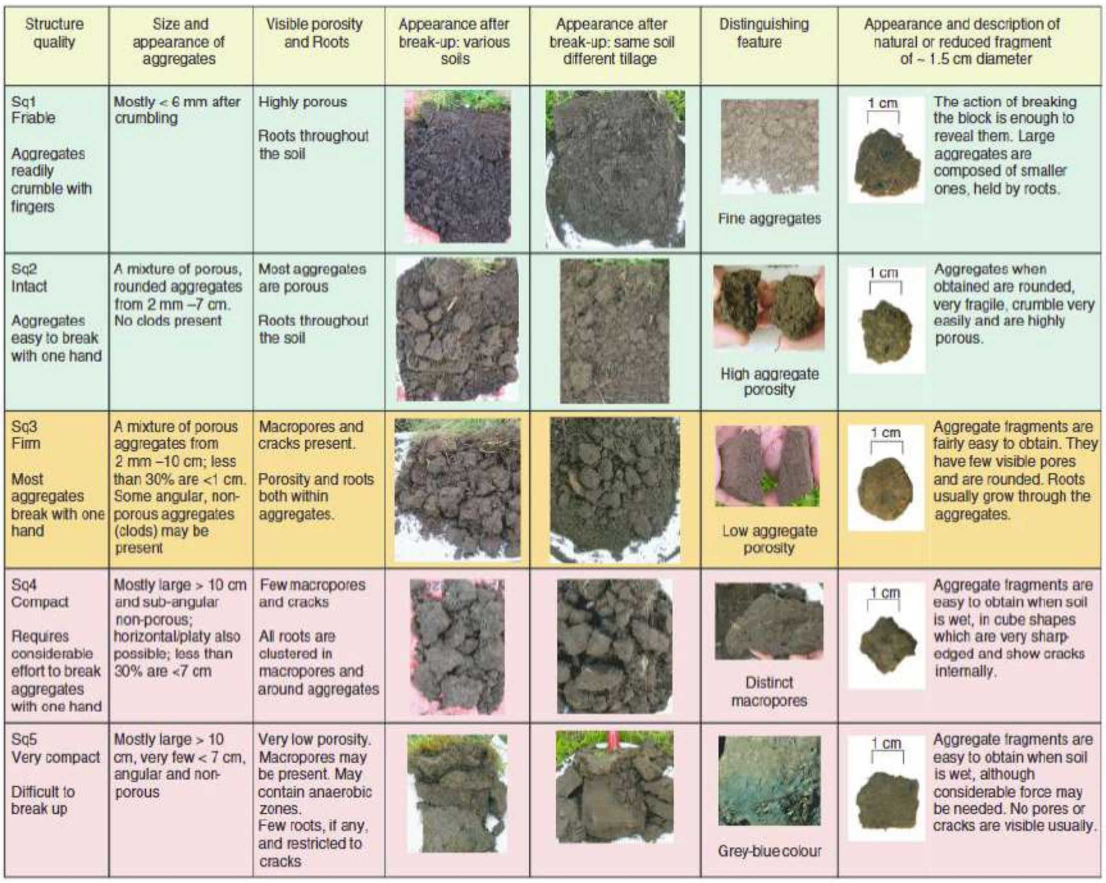
Material and Methods

Soil samples were collected from 50 different points in Isparta under different land uses (dry and irrigated agriculture). Soil samples were taken from a depth of approximately 0-30 cm. VESS scores were obtained for three different depths (0-10, 10-20, 20-30 cm), and the VESS was calculated as 0-30 cm.

$$\mathrm{VESS} = \sum_{i=1}^{n} \frac{\mathrm{SqiTi}}{\mathrm{TT}}$$

Sqi: The score of VESS, Ti:Thickness of soil layer, TT: total thickness

The scores range from 1 to 5. 1- Very good: The soil is loose, easily broken by hand, and has high porosity. 5: Severely degraded structure: Hard, dense, layered structure, no pores, difficult to break up (Figure 1).



Improved chart. This chart can be downloaded from http://www.sac.ac.uk/vess.

Figure 1. VESS score chart

Soil Analyses

Soil samples brought to the laboratory were air-dried and then passed through different sieves to be used in different analyses. The distribution of textural fractions (sand, clay, silt) in the collected soil samples was determined using the Bouychous hydrometer method (Burt, 2014). Additionally, wet aggregate stability (Kemper and Rosenau, 1986), clay content (Özdemir, 2002), dispersion ratio (Lal, 1988), Structural Stability Index (Leo, 1963), and mean diameter average (2, 1, 0.5, 0.25, 0.106, 0.053 mm) were determined.

Linear relationships were established between the VESS scores determined in the field and the erosion susceptibility parameters obtained from laboratory analyses. Descriptive statistics and correlation matrices of the data set were determined using the Minitab 16 software package.

Results and Discussion

Soil texture classes are CL,C, SİC, SCL, SL, L. Soil texture is generally loamy and heavy (Figure 2). VESS scores exhibited a positive relationship with the clay and silt content of soils and a negative correlation with sand content (Figure 3, 4, 5). In the field study, especially in sandy-textured soils, the soil is easily disrupted, and VESS scores were generally determined to be low. So a negative relationship is expected. Clay type is more important than clay content percentage in aggregate formation and swelling, hardness, Clay can negatively affect structure. When not interacting with organic matter or under intensive tillage and compaction conditions. Silt alone does not bind aggregates, but it does by interacting with clay and organic matter. Aggregate is formation. There are studies indicating that VESS scores may increase as clay content increases and that sodium content is also quite effective (Ball et al., 2007).

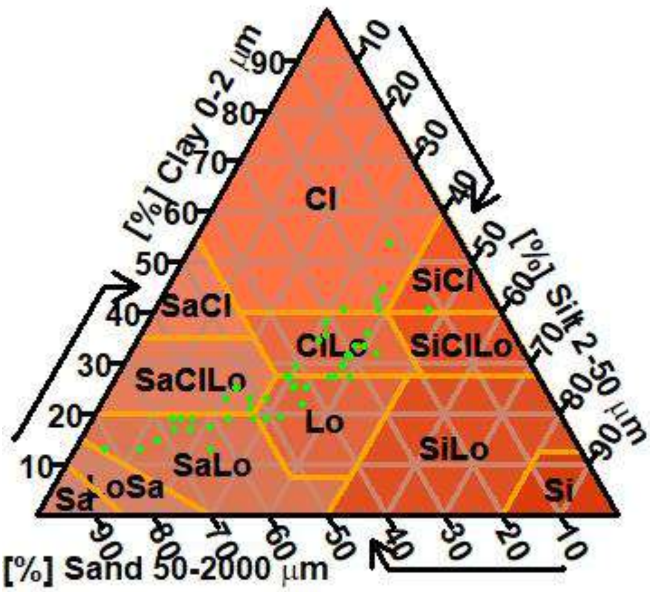


Figure 2. Soil Texture class

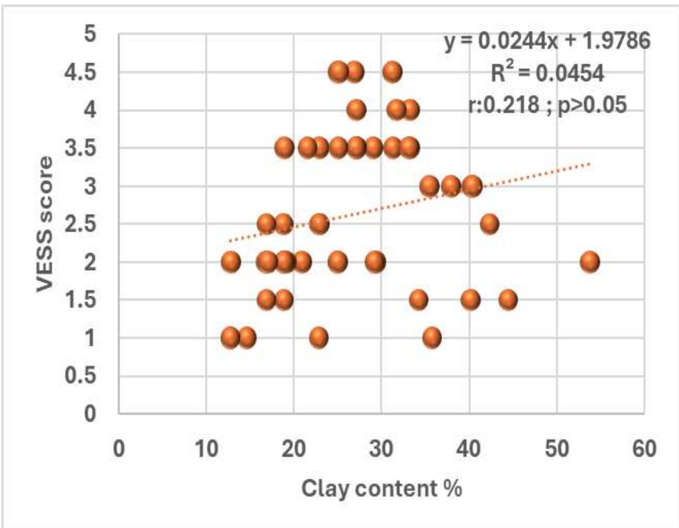


Figure 3. Clay content and VESS scores relationships

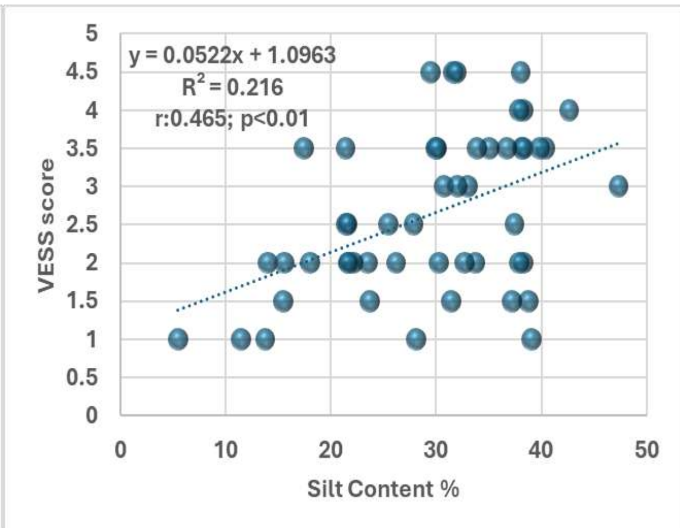


Figure 4. Silt content and VESS scores relationships

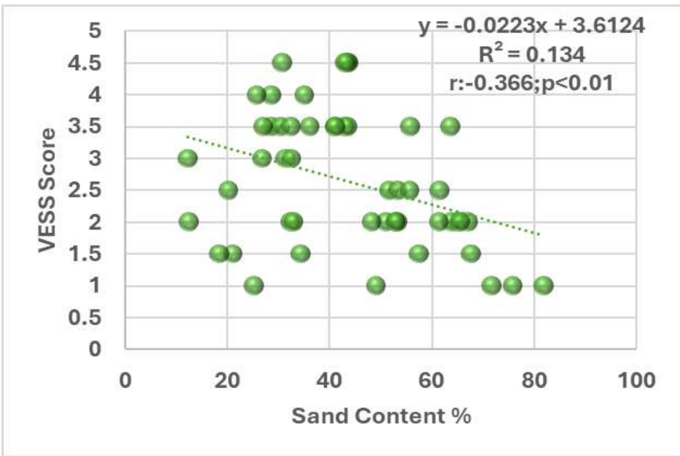


Figure 5. Sand content and VESS scores relationships

Soil organic matter content varies between low and good. There is no salinity problem in the soil. Lime content is usually high. No significant correlation was found between organic matter and VESS (Figure 6). The low correlation is due to: the narrow range of variation, every fraction of organic matter is not effective in aggregation, it is generally high at the surface (0-10 cm), but the soil sample represents 30 cm. Evaluating the correlation of only the surface soil may reflect a higher correlation. A positive correlation was obtained between EC and lime content and VESS scores (Figure 7, 8) . However, it was not found to be statistically significant. Calcium binds with clay and OM to form stable aggregates. With increasing salinity, if the dominant salts are Ca^{2+} or Mg^{2+}, increase the stability and hardness of aggregates. This positively affects the VESS score.

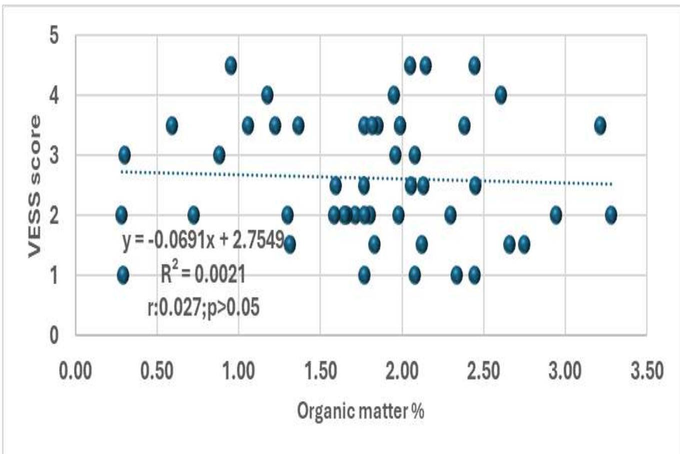


Figure 6. Organic matter content and VESS scores relationships

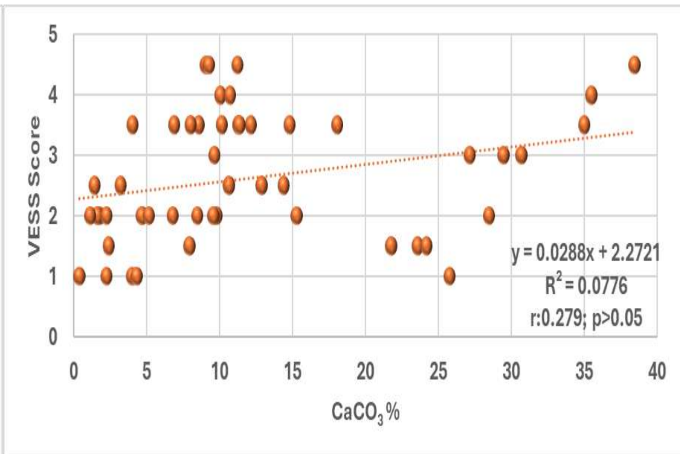


Figure 7. $CaCO_3$ content and VESS scores relationships

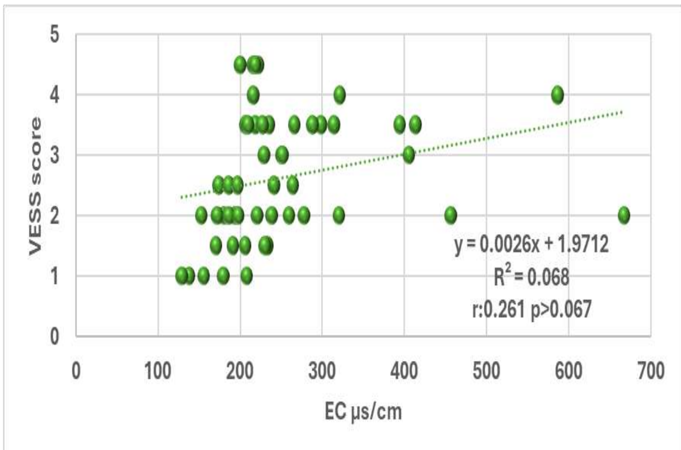


Figure 8. EC content and VESS scores relationships

VESS scores are positively correlated with penetration resistance and bulk density (Figure 9). BD and PR are effective in reflecting the soil compaction status." Since VESS visually assesses compaction, porosity and aggregate integrity of the soil, increasing compaction and density values lead to higher VESS scores.

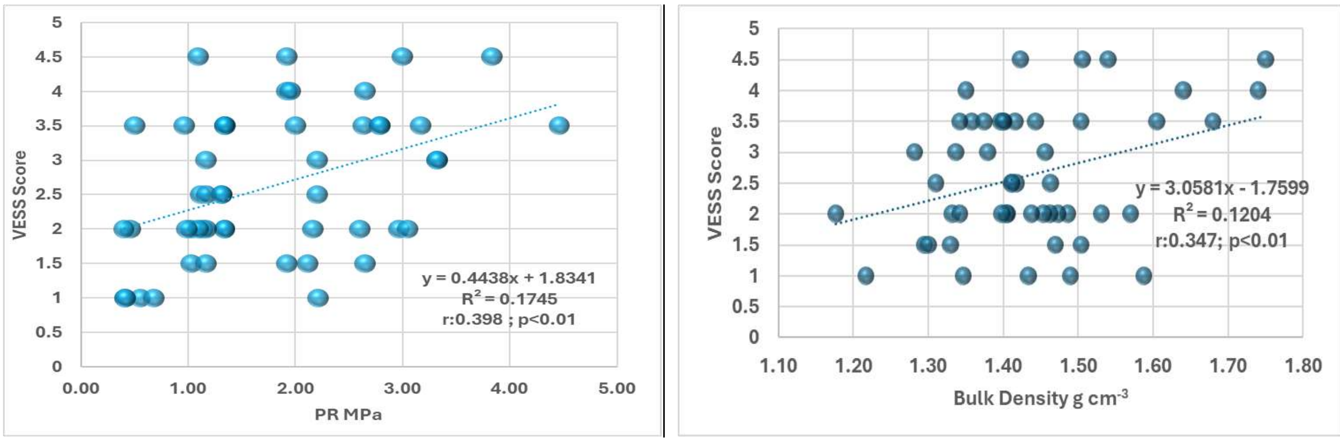


Figure 9. Bulk density, PR and VESS scores relationships

A positive correlation was found between the dispersion rate and the VESS. Aggregate integrity is impaired in soils with high dispersion rates. The VESS evaluation conducted in the field will also higher scores (Figure 10). Higher VESS scores indicate more durable and fragmentation-resistant aggregate structures. A low correlation was found between wet aggregate stability and VESS scores (Figure 11). Wet aggregate stability is typically measured under laboratory conditions at specific aggregate sizes and may not fully reflect field heterogeneity. Dexter (2004) reported that aggregate sizes and aeration affect root development and structural status.

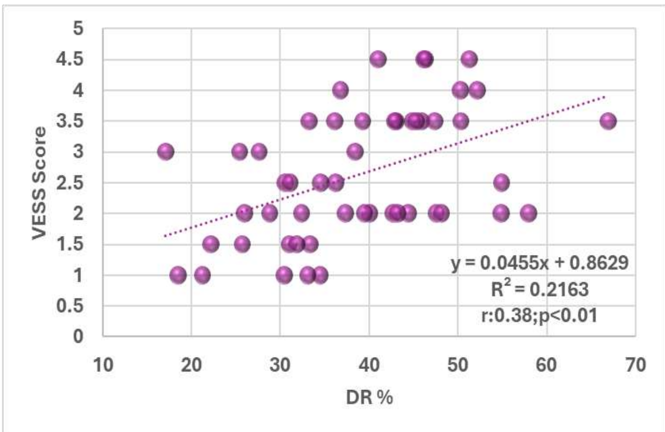


Figure 10. Dispersion rate and VESS scores relationships

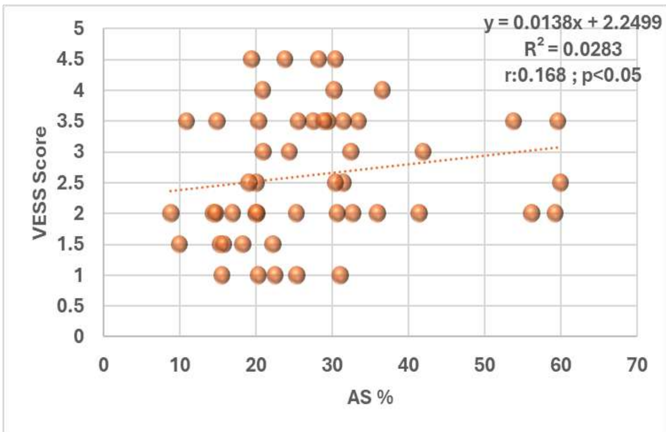


Figure 11. Aggregate stability and VESS scores relationships

No significant relationship were found between the structural stability index, mean diameter weight and VESS. As the soil structure deteriorates (VESS score increases), the integrity of the aggregates deteriorates → the mean diameter weight decreases. As the stability index increases, the resistance of the aggregates to disintegration increases, thus increasing the VESS (Figure 12, 13).

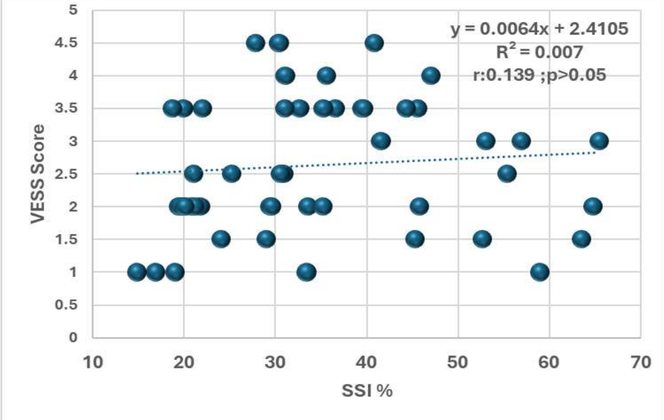


Figure 12. structural stability index and VESS scores relationships

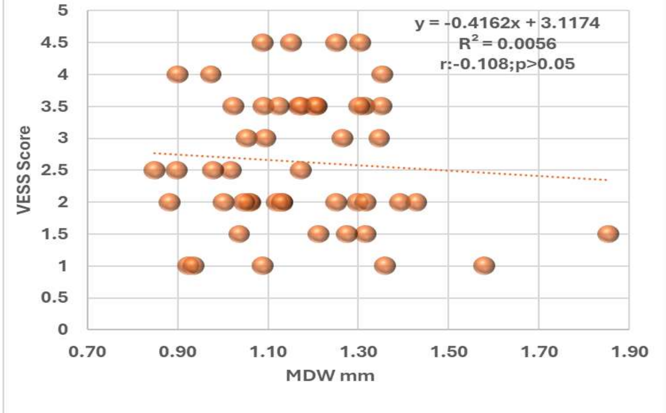


Figure 13. Mean diameter weight and VESS scores relationships

Conclusion

VESS is a particularly sensitive indicator for capturing dynamic physical and chemical changes (compaction, dispersion, salinity) under field conditions. Soil genetic properties usually can't reflect field structural observations in some cases. Using VESS, they can easily monitor the compaction, fragmentation, or structural degradation of their fields and take preventative measures without needing laboratory analysis (especially with VESS scores of 4-5). In the future, VESS could become an important decision-support system for monitoring soil health and guiding sustainable agricultural practices, supported by simple monitoring. İn regions with problems such as soil compaction, improper tillage and irrigation issues, regional specific sustainable tillage recommendations can be developed. Soil management and cultivation practices can be suggested, and tillage depths can be adjusted.

Acknowledgements

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