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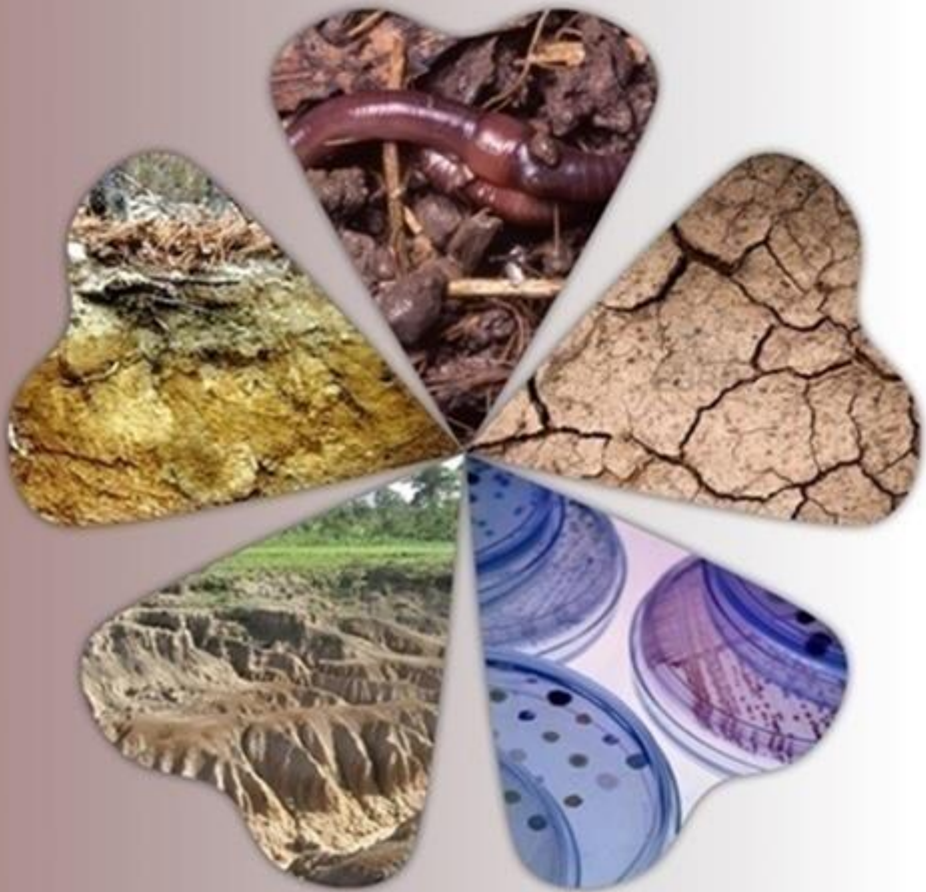

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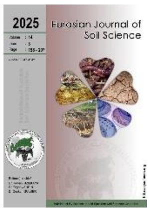

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Eurasian Journal of Soil Science (EJSS) is the official Journal of the Federation of Eurasian Soil Science Societies. EJSS is a peer-reviewed, open-access journal dedicated to publishing high-quality research articles, critical reviews, and short communications in the broad field of soil science, including soil-plant interactions and environmental soil studies. The journal serves as a platform for global and regional theoretical and experimental research on soil science, fostering knowledge exchange among researchers, professionals, and policymakers.

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The effectiveness of bio-treatment on licorice (*Glycyrrhiza glabra*) productivity and soil restoration in saline ecosystems

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Abstract

Licorice (Glycyrrhiza glabra) is a highly valued medicinal plant, widely used in the pharmaceutical industry, therefore its natural habitat is dwindling sharply in the Aral Sea region. Considering the essential role of this salt-tolerant halophyte for ecosystem functions, urgent actions are needed to help restore degraded landscapes. The experiment was conducted during vegetation seasons 2022 and 2023 in saline lands (EC~10-12 dS m^{-1}) of Karakalpakstan using a split-plot design with an RCBD arrangement. The effects of seed bio-treatments, i.e. BIST, Zamin, and Geogumat on the root yield of licorice and its quality as well as microbial community composition in the root rhizosphere were studied in abandoned saline land. Results indicate that the Geogumat application increased the seed germination by 24.3%, root biomass by 37% and glycyrrhizin content by 12.7%. Similarly, Zamin and BIST also significantly enhanced these parameters compared to the control under soil salinity stress. It has been found that licorice as a legume interacted with N_2-fixing microbes, thereby significantly increased NPK availability in the soil. The root and shoot biomass increased in response to the seed bio-treatments, most likely because of improved soil microbial activity. The presented eco-friendly research endeavors in this study might be considered as a significant solution to convert abandoned saline lands into sustainable agricultural production, thereby reducing the negative impacts of climate change and restoring ecosystem functionality.

Keywords: Licorice, biofertilizers, saline soil, arid environment, beneficial bacteria, ecosystem sustainability.

Introduction

Land degradation remains a crucial issue for Central Asia, requiring sustained collaborative efforts to enhance soil health, improve land management, and strengthen resilience to climate impacts. Meanwhile, the increasing severity of soil salinization is leading to serious ecological, health, economic and social challenges, particularly in the Aral Sea regions (Ahn et al., 2024).

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Transforming salt-affected lands into productive agricultural systems can be achieved through the introduction of salt-tolerant crops and innovative land management practices. Various eco-friendly strategies have been tested in arid regions such as Karakalpakstan, to encourage the widespread adoption of soil restoration practices. Over the past 30 years, the proportion of strongly and moderately saline lands in the region has expanded from 38.5% to 58.4% due to the Aral Sea tragedy. Furthermore, hundreds of tons of salt are carried annually by wind and water from abandoned saline areas to adjacent irrigated farmland, increasing the risk of soil salinization. Currently, approximately 91% of irrigated land is affected by salinity, with 48% classified as highly saline (12-16 dS/m) (Rustamova et al., 2023). As a result, significant efforts directed towards developing and implementing new management strategies to enhance crop yield and soil health in salt-affected and marginal fields (Nurbekov et al., 2023).

During the Soviet era, agricultural production in Karakalpakstan was largely concentrated on cotton and wheat cultivation. The absence of organic matter incorporation back into soils and cultivation of non-legumes associated with the overuse of chemicals has had detrimental implications, such as reduced humus content and micronutrient levels in the soil.

The use of halophyte legumes in saline soil restoration is an innovative and cost-effective approach of reclaiming abandoned irrigated lands. It has been proved that developing highly productive fodder systems through the introduction of palatable halophytes can enhance the productivity of saline soils, providing revenue to farmers with limited resources. Halophytes are ecologically and physiologically distinct salt-loving plants that may produce significant green biomass and grain yields under saline conditions (Fozi et al., 2024).

Licorice (Glycyrrhiza glabra) is a perennial herbaceous halophyte, inherently more resilient to salt and drought stresses than many other desert plants originated in Central Asian rangelands. This halophyte plant grows well in fragile ecological environments because of its deep root system. It has a significant commercial value due to its strong nutritional profile. Therefore, it is widely used in medicine, cosmetics, and industry. The demand for licorice grown in Uzbekistan has gradually increased since 2000, owing to its pharmacological qualities, which include glycyrrhizin and oleanane-type triterpene saponins. As a result, its native habitat declined rapidly in the deltas of the Amudarya and Syrdarya rivers in Uzbekistan (Khaitov et al., 2021).

Although licorice is known to be drought and salt-tolerant, the plant's reaction to these stresses differs according to its genotype and developmental stage. Major constraints are salt stress and water deficiency at the early licorice vegetation stages that can interfere with herb seed germination, impact seedling development, and potentially cause death through long-term suppression (Bao et al., 2024).

Soil beneficial bacteria facilitate plant growth, as a component of climate-resilient agriculture, has significant promise for rehabilitating abandoned saline lands. Licorice with soil beneficial bacteria can resist environmental stresses, improve soil's physical and chemical characteristics, enrich it with organic matter, and restore soil biological activity (Begmatov et al., 2020). These proactive measures support sustainable farming by increasing nutrient availability, improving soil health, and enhancing crop productivity, while also balancing environmental and ecological objectives. A key priority is improving soil health with a strong emphasis on sustainable natural resources management and resilience. Furthermore, the application of modern biotechnologies generate added value by creating a more suitable healthy environment for plant survival.

However, while extensive research has been conducted on bio-treatments for leguminous and medicinal plants, studies specific to licorice grown in saline soils are limited. Even though the region is suitable for long-term sustainable licorice production, licorice faces abiotic and biotic challenges, especially during the initial growth period. Therefore, this study aimed to examine the effectiveness of bio-treatment agents on licorice productivity such as root yield and phytochemical content as well as soil microbiological activity, revitalizing the saline dryland ecosystem.

Material and Methods

Climate and soil characteristics

The trial was established in agro-climatic zones in Nukus district at the Experimental Station of the Institute of Agriculture and Agrotechnologies of Karakalpakstan during the 2022-2023 vegetation seasons. The climate of the area is full of contrast. It is an arid Karakalpakstan area with very hot (> 40°C) and dry summer in July-August and severe cool winters (< -20°C) in January (Figure 1). This region experiences notable temperature variations throughout the year. There has also been an increasing trend in the number of sunny days with high temperatures in addition to a general trend of increasing degrees of aridity and salinity. Even daily temperature fluctuations can be substantial with hot days and cool nights. The extreme environmental conditions pose difficulty for year-round cropping, which is aggravated by very little rainfall, averaging around 90-120 mm annually.

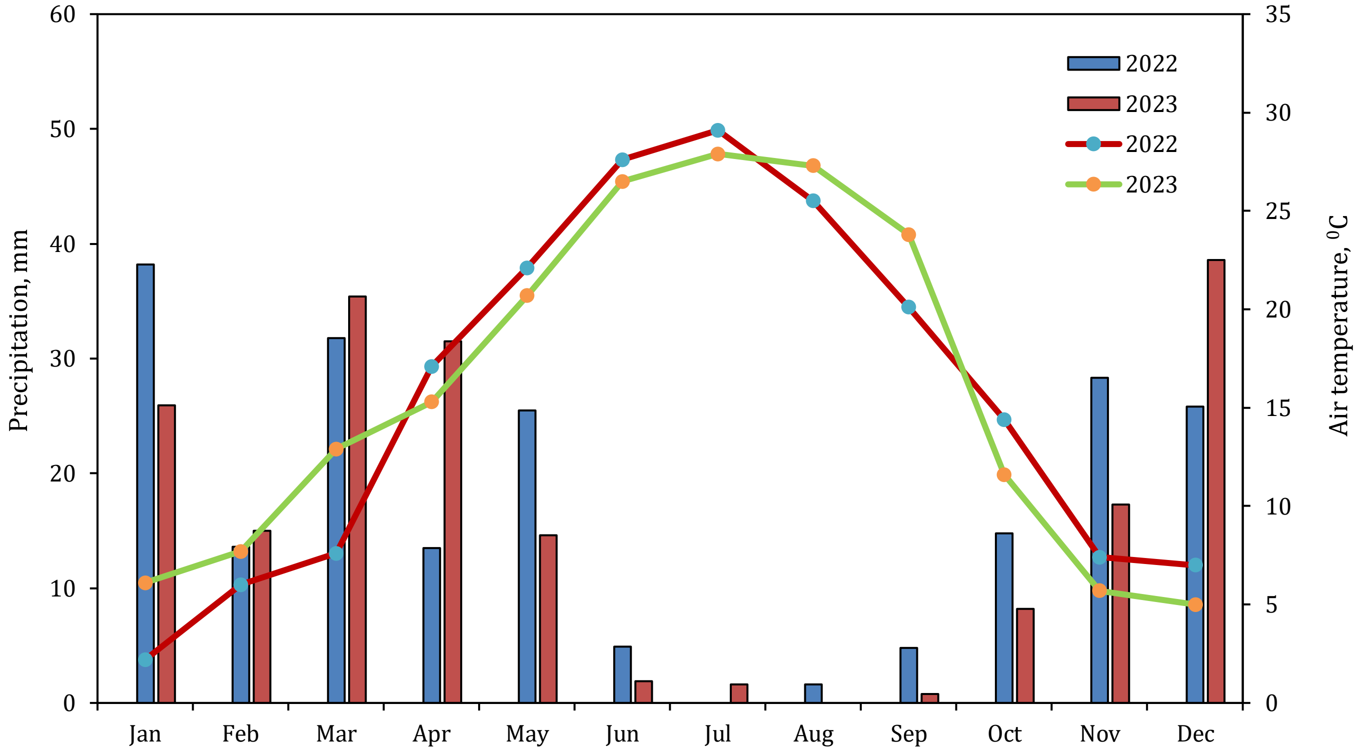

Figure 1. Climate records in Karakalpakstan, air temperature (in curves) and precipitation data (in columns) during 2022-2023.

Soil in this area is highly saline with an electrical conductivity (EC) ranging from 12 to 16 dS m^{-1}. The pH of the soil was in the range of 8-8.5 and had loam texture at the top 0- 17 cm and Silt loam at 17-150 cm soil depth (USDA classification). The humus content in the arable layer is 0.626%, in the lower horizons 0.277%, and in the parent rock 0.172%. The dominant cations were Na^+ and Mg^{2+} with wide differences in their concentrations. The levels of sodium absorption ratio (SAR) were in the range of 4.38 to 11.43, suggesting that groundwater is marginal in its characteristics.

The experimental field was divided into small sections (0.03-0.05 ha) to carry out the salt leaching process with 2500-3200 m^3/ha water. The field was leached three times as per the traditional cropping practice (the first one was on February 21 and the second one was on March 14). The third and last leaching activities were carried out at the beginning of April. After the leaching activity, the experimental plot was deep plowed (30 cm depth) and chiseled one more time and root residues were removed manually. Mineral fertilizers were ($N_{100}P_{140}K_{80}$) uniformly applied to the fields before seed planting. Usually, after the irrigation of the field soil gets harder in clay loam plots. Therefore, it is necessary to use organic manure to make soil softer if available. Considering the local climatic conditions, weeding will be carried out by hand during the crop vegetation period when required. The high salinity levels in the soil and groundwater enforce the need to apply furrow irrigation, also known as flooding irrigation. Furrow irrigation was applied three times during the vegetation period at a norm of 800-1000 m^3 identical to all plots, totaling 2400-3000 m^3 per hectare.

Biofertilizers and their use

Bacterial fertilizers BIST (prepared on the base of Pseudomonas putida Pp-1 consists 1×10^7 CFU/mL), Zamin (Azotobacter Chroococcum consists 5×10^9 CFU/mL) were provided by the Institute of Microbiology, Academy of Science of Uzbekistan.

Geogumat consisted of a consortium of beneficial soil bacteria including more than 20 microorganisms, i.e. Bacillus megaterium, Bacillus mucilaginosus, Basillus Subtilis and etc. It is liquid of 12% organic fertilizer and formed by microelements. There is humic acid at least 32% and Fulfa and other organic acids consist of at least 25.0%.

Licorice seeds (cv. Tong shabnami) were provided by Botanika Scientific Research Institute, Tashkent, Uzbekistan.

When the ground warmed up sufficiently under the sun, seeding began on April 22–24. Before starting experiments, the seeds were sorted by eliminating broken, small and infected seeds. Surface-sterilized licorice seeds in the solution of 75mL chloride + 25mL water for 2-3 min, thoroughly rinsed 5 times with sterile water.

Then the inoculation process continued for 30 min with appropriate biofertilizers following the standard procedure before planting the seeds in the experimental plots. In order to avoid cross-contamination between the biofertilizers all the required protection measures were taken into consideration. The seed planting procedure was conducted manually in this case study at standards of 10 kg/ha. To increase germination and produce robust seedlings, the field was irrigated following the seeding procedure. Before second furrow irrigation, the norm remaining of N and 20% of P and K fertilizers were delivered after weeding and cultivation activities.

Experiment design

The selected field was abandoned from agricultural production for the last 15 years, hence heavily infested with wild vegetation. A lot of effort in terms of heavy machinery like bulldozer was used to bring back this field into shape for crop cultivation. The experimental field with a size of 135 x 100 m was laser leveled at the beginning of the land preparation process.

The experiment was set out in three replications using a randomized complete block design (RCBD) with a split-plot treatment structure. The experiment's total land area was 0.12 hectares, of which each plot measured 96 square meters (4.8 m x 20 m, or 8 rows, each measuring 0.6 m in width and 20 m in length). Each plot's accounting area measured 24 square meters. These field trials were carried out in compliance with the "Methods of Field Experiments" (UzPITI, 2007).

Data collection and chemical analysis

The parameters of seed yield, root mass, and fodder productivity were measured on a 1 square meter area in each plot. Two phases of plant density were measured: following seedling emergence and at the end of the vegetation period. The 25 tagged plants in each plot were subjected to agronomic measurements, including plant height, weight, and the quantity of leaves and pods.

The number of leaves, plant height, biomass of plants, particular leaf weights (leaf dry weight, leaf: shoot dry ratio, shoot dry matter), leaf area, and chlorophyll content were all measured during the field trials. At the end of each season, root mass was calculated by using the monometer method which is conducted by digging up to one meter and then drying in a drier apparatus for 72 hours at 700C. Using specialized equipment, 20 samples on 1 cm2 were taken to determine the leaf area.

Plant extracts, i.e., ash, glycyrrhizic acid, extractive compounds and flavonoids were determined by spectrophotometry in the Mettler_Toledo laboratory complex. Extraction method of glycyrrhizic acid analysis was as follows: samples extracted with 70% ethanol or methanol-water (50:50 v/v) using ultrasonic or Soxhlet extraction. Hydrolysis with HCl was done to release glycyrrhizic acid from glycosides. The absorbance was measured at 254 nm using HPLC-UV for direct UV absorption.

The selection of actinomycetes, ammonifiers, and oligonitrophils as indicators of soil microbial activity is based on their critical ecological roles in nutrient cycling, soil fertility, and organic matter decomposition. Several microbiological analyses were conducted to determine the microbial activity of soil samples at the beginning and end of the experiment. The serial dilution plate method was employed to observe total numbers of actinomycetes, ammonifiers and oligonitrophils by counting colony-forming units (CFUs) on agar plates (25-30^{o}C) during 5-7 days. The medium used for the enumeration of total numbers of spores and micromycetes was soil agar.

Data analysis

A one-way ANOVA tool (CropStat statistical software program) was used for statistical analysis of collected data during the 2022-2023 vegetation seasons. Tukey's least significant difference (LSD) test was employed to determine the significance of mean value differences and all experiments were conducted in duplicate. Microsoft Office Excel 2007 was used to create the graphics.

Results

Effect of biofertilizers on soil nutrient and microbial content

The application of the biofertilizers as a seed treatment for licorice cultivation significantly increased soil humus content and total form N and P as compared to the control group (Table 1).

Table 1. Soil chemical analysis.

Soil depth (cm)	Soil ECe (dS/m)	Soil pH	Exchangeable Na percentage (ESP)	Total forms (%)		Exchangeable forms (mg/kg)		
				Humus	N	NO_3	P_2O_5	K_2O
Before the experiments								
0-15	15.6b	6.1	0.4	0.6a	0.010	12.2c	16.2b	522a
15-30	17.2a	6.5	0.4	0.6a	0.015	10.3c	10.8c	500b
30-50	17.8a	7	0.8	0.5b	0.001	7.12c	5.12e	484c
The BIST plot								
0-15	12.5d	7.1	0.7	0.7a	0.012	18.6b	18.4a	518a
15-30	13.4c	6.8	0.8	0.6a	0.014	15.1b	6.67	324d
30-50	13.8c	6.4	0.8	0.5b	0.009	12.3c	12.4c	226f
The Zamin plot								
0-15	11.1e	7.6	0.16	0.6a	0.009	17.0b	16.2b	572a
15-30	11.9e	7.6	0.19	0.6a	0.016	14.6b	10.8	500b
30-50	13.1cd	7.7	0.3	0.5b	0.009	10.1c	8.3d	494c
The Geogumat plot								
0-15	9.2 g	7.7	0.1	0.7a	0.031	22.8a	19.6a	548a
15-30	10.2f	7.4	0.99	0.7a	0.019	16.1b	14.3c	341d
30-50	11.8e	7.5	0.8	0.5b	0.006	11.7c	9.4d	263e

Means of three replications (n = 3) separated by lowercase letters (a and g) in each column are significantly different at *P*≤5% according to the Tukey's LSD test.

The exchangeable NO_3, P_2O_5 and K_2O contents were enhanced significantly with the application of the licorice seed treatments, thereby increasing soil fertility parameters.The effect was more pronounced at the Geogumat biotreated plot, exhibiting the highest soil fertility index. Whereas soil salinity indicators decreased significantly in the plots where licorice seeds were planted with bacterial inoculations. The highest effect was seen in the Geogumat plot followed by Zamin and BIST treatments.

Likewise, soil chemical properties were substantially affected by the seed bio-treatments. Particularly, exchangeable forms of NO_3 value increased by 52.5, 39.3 and 144.3% respectively compared to the control value at 0-15 cm soil horizon under BIST, Zamin and Geogumat bio-treatments. Similarly, P_2O_5 and K_2O parameters were higher significantly than that of the control group. In terms of humus content, there was some increase even though it did not reach to a significant point during the two-vegetation period.

As Table 2 shows, the seed bio-treatments increased soil microbial activity, i.e., ammonifiers, spores, oligonitrophils, micromycetes, actinomycetes. The application of Geogumat produced the greatest number of the aforementioned soil bacterial communities, followed by BIST and Zamin bio-treatments.

The humus content of the soil significantly improved as a result of these beneficial soil interventions. Similarly, the application of bio-treatments resulted in the greatest levels of total N and P. Increased nutrient availability keeps the ameliorative properties of the soil intact and revitalizes the ecology of the soil. Significant favorable connections were found between the bio-treatments utilized in this experiment and the soil's N cycle. In turn, exchangeable NO_3, P_2O_5, and K_2O concentrations are closely correlated with increasing the overall form of N in the soil.

Table 2. Quantity of microorganisms in the licorice root rhizosphere as affected by the bio-treatments (averaged across two growth seasons).

Treatments	Ammonifiers	Oligonitrophils	Micromycetes	Actinomycetes
At the beginning of the experiment				
	$5.2x10^6$d	$3.1x10^4$d	$5.5x10^3$c	$4.2x10^4$d
At the vegetation period				
Control	$4.5x10^6$c	$4.5x10^5$c	$9.1x10^3$d	$7.5x10^4$c
BIST	$6.3x10^7$b	$2.7x10^6$b	$3.7x10^4$b	$3.4x10^5$b
Zamin	$3.5x10^6$c	$5.2x10^5$c	$1.5x10^4$d	$3.5x10^5$b
Geogumat	$7.5x10^8$a	$3.5x10^7$a	$7.5x10^4$a	$4.5x10^5$a

Means of three replications (n = 3) separated by lowercase letters (a and c) in each column are significantly different at *P*≤5% according to the Tukey's LSD test.

Early research supported a similar phenomenon, demonstrating that certain macronutrients are stoichiometrically related to preserving ecosystem balance (Aziz et al., 2013). This study demonstrated how the bacterial inoculant, when combined with legumes, increased the population and diversity of soil microbes in salt soils. A large number of soil microorganisms, which are essential to the nutrient cycling and ecosystem functioning of the soil, determine the majority of the accessible nutrient content of the soil (Hammerschmiedt et al., 2021). The seed inoculation produced the highest microbial activity, indicating that the bacterial injection improves the biological condition of the soil.

Licorice fodder yield parameters

Table 3 shows the seed germination and yield production under salt stress. The seed germination increased by 34.1, 44.6 and 57.2% under BIST, Zamin and Geogumat treatments, respectively. Likewise, the fodder yield index was significantly higher in the seed biotreated plots as compared to the control.

Table 3. Effect of biofertilizers on seed germination, fodder yield and quality parameters.

Treatments	2022				2023		
	Seed germination, %	Fodder yield	Food units	Digestible protein	Fodder yield	Food units	Digestible protein
Control	42.3d	143.3c	89.8c	22.0c	189.0d	112.2c	23.8c
BIST	56.7c	185.5b	98.2b	23.3b	220.4c	122.7b	25.1b
Zamin	61.2b	196.3ab	98.6b	24.8ab	231.4b	123.2b	25.2b
Geogumat	66.5a	211.4a	104.3a	25.7a	266.7a	128.6a	25.6a

Means of three replications (n = 3) separated by lower case letters (a and d) in each column are significantly different at *P*≤5% according to the Tukey's LSD test.

The highest increase in fodder yield was observed in the Geogumat variable, followed by Zamin and BIST, exhibiting 47.5, 36.9 and 29.4% increases as compared to the control group. This mode was seen in the values such as food unit and digestible protein in the plant shoot which were significantly higher than that of the control in the 2022 season.

Table 4. Effect of different biofertilizers on licorice fodder productivity and quality.

Treatments	Protein	Oil	Cellulose	Ash	Ca
Control	18.0c	17.0c	26.8c	7.07c	2.00c
BIST	18.9b	17.9b	27.5b	8.00b	2.08b
Zamin	19.1b	18.0ab	28.5ab	8.93a	2.10b
Geogumat	21.1a	18.2a	29.0a	8.94a	2.20a

Means of three replications (n = 3) separated by lowercase letters (a and c) in each column are significantly different at *P*≤5% according to the Tukey's LSD test.

A similar trend was observed in terms of fodder protein, oil, cellulose, ash and Ca parameters. Whenever, the highest parameters were monitored in the Geogumat treatment, followed by Zamin and BIST variables.

Under the Geogumat application, the difference in the fodder protein was substantially improved, while the increase was 16.5% higher than that of the control. While Zamin and BIST increased fodder protein parameters by 6.1 and 5%, exhibiting a significant difference as compared to the control values.

The absolute contents of fodder oil, cellulose, ash and Ca demonstrated an increasing trend under the applied bio-treatments, reaching to significant level in most cases.

Effect of biofertilizers on the root yield and phytochemical contents

Analysis of variance revealed that the used licorice seed bio-treatments led to a significant increase in root yield and its quality indicators (Table 5). The average root yield in the Geogumat, Zamin and BIST treatments were elevated by 37, 23 and 16%, respectively than that of the control. Similarly, secondary metabolites were produced significantly higher with the seed bio-treatments under saline environmental conditions.

Table 5. Licorice root yield and phytohemical changes due to biofertilizers

Treatments	Average root yield, t ha^{-1}	Total ashes, %	Glycyrrhiza acid, %	Extractive substances,%	Flavonoids, %	Quality, %
Control	30.0d	4.89b	7.00b	39.50b	2.00b	0.175b
BIST	34.8c	5.15a	7.81a	40.05b	2.23ab	0.187a
Zamin	36.9b	4.95b	7.82a	40.08b	2.24ab	0.180b
Geogumat	41.1a	5.23a	7.89a	41.20a	2.29a	0.191a

Means of three replications (n = 3) separated by lowercase letters (a and d) in each column are significantly different at *P*≤5% according to the Tukey's LSD test.

Meanwhile, the contents of glycyrrhizin were higher in the biotreated variables, reaching a significant level as compared to the control. Particularly, the maximum glycyrrhiza acid was achieved under Geogumat, followed by Zamin and BIST seed treatments, exhibiting 12.7, 11.7 and 11.5% increases over the control values. This two-year analysis found that greater licorice root components, i.e. total ashes, extractive substances, flavonoids parameters were achieved with the seed bio-treatment applications.

Discussion

The effectiveness of licorice inoculation in saline environment

Soil degradation in the Aral Sea region is caused by a number of reasons, including (i) improper irrigation and badly maintained drainage systems, (ii) waterlogging and subsequent salinization, and (iii) salt dispersion from dust storms due to the Aral sea crisis, that can reach a distance of 500 km (Begmatov et al., 2020; Makhanova and Ibraeva, 2025). Fine particles of sodium bicarbonate, sodium chloride, and sodium sulfate are carried by the wind and have an adverse effect on agricultural lands, crops and natural vegetation. Excessive amounts of these salts have a dangerous impact on soil health and further deteriorate plant growth and development, lowering crop production and harming food security (Chernyh et al., 2024). Considering local environmental characteristics some prerequisites must be taken into account for crop selection, such as adaptability, pest and disease resistance, marketability and profitability, accessible technology, and agricultural systems to reduce a high risk of climate change, soil salinity, and drought. Whereas, applied on-farm management techniques should provide profitability and sustainability.

Licorice production in abandoned lands in this area as a model of green technologies can contribute to a more sustainable agricultural system, promoting soil health and productivity. In addition to the theoretical discussion of how biofertilization affects licorice quality under salt stress, this study exhibited practical justification for the restoration of soil health and ecosystem functions. In degraded dryland systems, biotic obstacles, such as reduced beneficial soil microbial populations, and abiotic barriers, such as less moisture and nutrient availability and soil erodibility, frequently restrict ecosystem recovery (Chaudhary et al., 2020; Esmaeili et al., 2024).

Although the demand for active soil restoration is increasing, little is known about how these methods might be applied most effectively to enhance soil health in degraded drylands across environmental gradients. To restore soil health in degraded drylands, soil-based restoration strategies have become more popular in recent decades (Faist et al., 2020; Román et al., 2021). Nevertheless, the effectiveness of various soil treatments in encouraging the restoration of soil function has varied. According to a recent study, biocrust inoculation improved aggregate stability but straw barriers and soil tackifiers did not, suggesting that some treatments may be more effective than others at enhancing soil health (He et al., 2021).

However, investigations on the role of bioagents in stimulating and alleviating salt stress for licorice production are important. Therefore, the effectiveness of up-scaling of licorice with bioinoculants was practiced in saline abandoned lands of Karakalpakstan. Despite the fact that licorice is an ingenious perennial legume that can withstand drought and saline pressures, crop producers do not cultivate it in subsistence farming systems. Achieving these aims and scaling up necessitates a change in the current environmental situation. If thorough salinity alleviation methods are not performed prior to planting, the salinization damage will be catastrophic for licorice species with medium- and high salt tolerance. Biological solutions are a practical answer to soil salinization restriction that will increase productivity and revenue generation. Previous studies also exhibited a tendency for the increase of licorice root yield quality parameters initially under salt and water stresses and then falling rapidly as the stress increased (Zhao and Li, 2023).

The planning method involved categorizing agricultural land based on production, taking into account a number of elements related to soil qualities and fertility. It is apparent that current agricultural intervention should be supported, and markets established accordingly.

In addition to the improvement of seed germination, root system development, and seedling growth, the used biofertilizers increased crop output by 15% to 20% and increased tolerance to environmental stressors. They also increased the efficiency of mineral fertilizers and the quality of the soil. The Geogumat application had the highest overall output as determined by total root biomass with a 30% increase over the control. This suggests that beneficial bacteria might be especially useful for encouraging the growth of licorice roots. A significant increase in yield was also observed in the compost-treated group, indicating that organic matter promotes the growth of root biomass.

With an average rise of 25%, licorice plants treated with bio-treatments demonstrated a considerable increase in root length when compared to the control group. This discovery emphasizes how biofertilizers can promote root development, most likely because of better nutrient uptake. Although it turned out that plants in the nitrogen-fixing bacteria group also had higher root biomass.

Nutrients turnover

Licorice requires fertilization as a fundamental factor to survive, grow and produce high-quality raw materials. Since licorice is a nitrogen-demanding crop, especially in its early stages, the N fixation ability provides an efficient alternative to synthetic fertilizers. Plant growth may still be stunted if fertilizers are delivered in low or excess amounts of what is needed (Khaitov et al., 2022).

The findings of this study demonstrated that the presence of salt-tolerant bacteria in licorice rhizosphere triggered the synthesis of a nitrogen fixation mechanism, which further enhanced plant tolerance to water and salt stresses and thereby enhanced the production of alkali and metabolites, so making a significant contribution to agroecology and development. Various studies have demonstrated the benefits of bio-treatment in improving growth parameters and enhancing plant resilience against biotic and abiotic stresses.

Licorice root exudates can promote the growth of beneficial bacteria by providing a carbon source. Certain beneficial bacteria, such as Bacillus and Pseudomonas, use these compounds to boost their growth and metabolism, which in turn can lead to improved nutrient cycling. The nutrient availability in the soil was greatly impacted by the seed inoculation applications. The amount of N and humus content in the soil primarily reflects the favorable relationship between licorice and microbes. The appropriate match between the two organisms, as well as anthropogenic and environmental factors, determine the fixed amount of N (Li et al., 2022).

Licorice's organic compounds can interact with soil minerals, enhancing nutrient solubility. Beneficial bacteria work with these compounds to break down organic matter, releasing nitrogen, phosphorus, and other essential nutrients that plants can absorb more efficiently. As this study shows, the induction of a nitrogen fixation mechanism in the presence of salt-tolerant bacteria reduced water and salt stress and enhanced the synthesis of alkali in medicinal plants, thereby improving soil health and agroecology. Some compounds in licorice can suppress pathogenic organisms, reducing disease pressure on plants. Beneficial bacteria work synergistically with these compounds to outcompete harmful pathogens, creating a healthier root-zone environment.

According to Abdiev et al. (2019) and Aşık and Arıoğlu (2020), this approach was previously well-documented and demonstrated that symbiotic N_2 fixation in legumes with competent rhizobia plays a crucial role in compensating for missing soil nitrogen (N) and potentially overcoming nutrient deficit (Khaitov et al., 2024). When combined, the revitalization of beneficial soil bacteria greatly benefited plant health and soil biological processes.

Biofertilizers are known to boost root-based crops by promoting nutrient uptake and increasing root length and surface area, which is consistent with studies in other leguminous and medicinal plants. This process enhances the soil microbiome's biodiversity, fostering a balance where beneficial microbes dominate over harmful ones. As it turned out this technique has a great value in alleviating nutritional deficiency in degraded lands.

Enhanced soil health and microbial diversity

When used with beneficial bacteria, licorice's organic material can enhance soil aggregation. The bacteria help bind soil particles together, forming stable soil aggregates that improve aeration, root penetration, and water retention (Dahnoun et al., 2024). This combination improves root establishment, reduces soil erosion and salinity stress. Licorice roots and plant residues contribute organic matter that, when broken down by beneficial bacteria, boosts soil organic carbon (Dang et al., 2021). This improves soil fertility, resilience to climate extremes, and the overall carbon sequestration potential of the soil (Li et al., 2018).

Integrating licorice extracts or residues with beneficial bacteria could be a sustainable soil management approach, enhancing nutrient cycling, soil fertility, and crop resilience against diseases and stress factors. The highest number of soil beneficial bacteria achieved with the seed bio-treatments suggests that this technique might be a key factor in restoring soil microbial activity. Soil study conducted at the end of the vegetation season showed that the use of biofertilizers enhanced the amount of organic matter and soil microbial activity, both of which are factors in better soil health. This implies that bio-treatment improves the soil environment and promotes plant growth, resulting in a more sustainable licorice cultivation system. Also, this study suggests that plant productivity is positively correlated with various groups of beneficial soil microbes interacting with the root rhizosphere.

The current study facilitated predictive knowledge in improving the ecological contexts in which soil-based restoration treatments may be most effective for enhancing soil health within the wide range of restoration outcomes. Numerous studies demonstrated the effect of salt-tolerant bacteria beneficial bacteria on medicinal plants under a stressful environment and assessed the change in the pharmacological value of the host plant's metabolites influenced by this flora (Verma et al., 2020; Sharma et al., 2022). The findings also indicated a positive impact on agroecology and soil health due to the presence of salt-tolerant bacteria in legume's rhizosphere that stimulate the nitrogen fixation mechanism, thereby enhancing alkali production in medicinal plants. Chua et al. (2019) discovered that microbial diversity had a greater influence on soil health, whereas effects may vary among ecosystems. According to Luna et al. (2016), organic additions including microbial compounds improved several elements of soil health more effectively than other approaches. According to other research, soil microorganisms significantly influence the success of restoration initiatives, supporting ecosystem functions and services (Wang et al., 2018).

The microbial activity was noticeably higher in the Geogumat group than in the control group, indicating increased root exudates, which may support greater rhizosphere microorganisms. Given this, microbes living in the rhizosphere of licorice can form a mutualistic association and coordinate their involvement in plant adaptations to stress tolerance. The plant growth dynamics treated with the organic substances improved substantially, suggesting the seed bio-treatments enhanced nutrient availability. It is important to point out that licorice cultivation technology with the appropriate seed treatment agents could also be commercialized in the future. As turned out in this study, these strategies ensure sustainable resource utilization, increasing crop areas and improving soil health without compromising water deficiency problems.

Conclusion

This study showed the importance of providing adequate seed bio-treatment to maximize licorice root yield while improving soil health, especially in abandoned saline lands. A more pronounced effect was observed when Geogumat was applied as a seed bio-treatment, generating the highest root yield of 41.1 ton ha^{-1} which was 37% higher than the control group. Along with Geogumat, Zamin and BIST seed treatments also played a crucial role in improving soil quality parameters, soil bacterial populations and nutrient availability, likely due to increased soil microbial diversity, nutrient turnover and better root-soil interactions under soil salinity.

Soil restoration with these biological approaches contributes to ecosystem recovery in drylands, preventing irreversible soil degradation in these fragile desert areas. In addition to recovering soil health. This approach also plays a critical role in supporting biodiversity, wildlife habitats and the health of the surrounding ecosystem. Further actions should focus on the integration of this cost-effective organic practice into large-scale agricultural production, applying it for salt-affected soil reclamation, and promoting its benefits to crop producers.

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Analysis of drought dynamics using SPI and SARIMA models: A case study of the Rostov Region, Russia

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Abstract

Based on precipitation data from six weather stations covering the period 1960–2024, this study presents a retrospective analysis of drought dynamics in the Rostov Region, Russia, and evaluates the potential of the SARIMA model for forecasting moisture regime fluctuations. The Standardized Precipitation Index (SPI) was employed as the primary drought indicator. Two key phases of crop development were analyzed: the vegetation initiation period (March–May), assessed using the three-month SPI of May (SPI-3), and the full active growing season (April–September), assessed using the six-month SPI of September (SPI-6). The Mann-Kendall test revealed a non-significant positive trend in SPI-3 across all stations, while SPI-6 trends were non-significant and varied in direction. The highest frequency of drought events, based on both SPI-3 and SPI-6, occurred during 1960–1969, with a general decline in subsequent decades. The lowest drought frequency was observed during 2010–2019. Notably, the frequency of extreme droughts has shown an increasing trend, posing significant risks to agricultural productivity. Although SARIMA modeling proved useful for short-term forecasting, its application was limited by unrealistic long-term projections and deviations from climatic norms. Consequently, drought forecasts were restricted to a two-year horizon. Nonetheless, the SARIMA approach remains a valuable supplementary tool for anticipating precipitation dynamics and drought events.

Keywords: Drought forecasting, Standardized Precipitation Index (SPI), SARIMA model, Vegetation Dynamics, Precipitation variability.

Introduction

One of the main manifestations of climate change is the noticeable shift in precipitation patterns. A key consequence of such changes is the increased frequency of drought events, generally defined as prolonged periods with significant precipitation deficit, accompanied by elevated temperatures and reduced air humidity (Wu et al., 2022). These events often have highly detrimental effects on ecosystems, agriculture, and other economic sectors. Therefore, the development of effective approaches for monitoring and mitigating drought has become a highly relevant and important task (Holgate et al., 2020).

Most drought assessment methods are based on analyzing the temporal dynamics of meteorological variables, with precipitation being the primary indicator. Drought characteristics are typically quantified using specialized indices (Van Ginkel and Biradar, 2021). Among the most widely used are the Palmer Drought Severity Index (PDSI), Reconnaissance Drought Index (RDI), Standardized Precipitation Index (SPI), and Standardized Precipitation Evapotranspiration Index (SPEI). Among these, SPI is particularly favored

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due to its simplicity—it requires only precipitation data—and its universality, allowing for standardized drought assessment across different regions and time periods. For this reason, it is recommended by the World Meteorological Organization (Svoboda et al., 2012). SPI assesses the deviation of precipitation over a specific time period from the long-term average (Bouaziz et al., 2021), converting the data into a dimensionless index that facilitates comparative drought analysis (Docheshmeh Gorgij et al., 2022).

This study focuses on the Rostov Region of the Russian Federation, where drought monitoring is of particular importance due to the region's critical role in national agricultural production. Situated in the southern part of the East European Plain and in the Pre-Caucasus region (Figure 1), the Rostov Region is characterized by unstable moisture conditions, dry and hot summers, and relatively snow-deficient winters. Studies indicate that climatic conditions represent the primary risk factor for agriculture in this area (Lukyanets and Bragin, 2021). In particular, reduced precipitation and the resulting frequent droughts during the growing season are identified as major causes of crop failure (Gudko et al., 2022, 2024). Moreover, projections suggest an increasing trend in aridity across southern Russia, including the Rostov Region, under ongoing climate change scenarios (Kattsov et al., 2008).

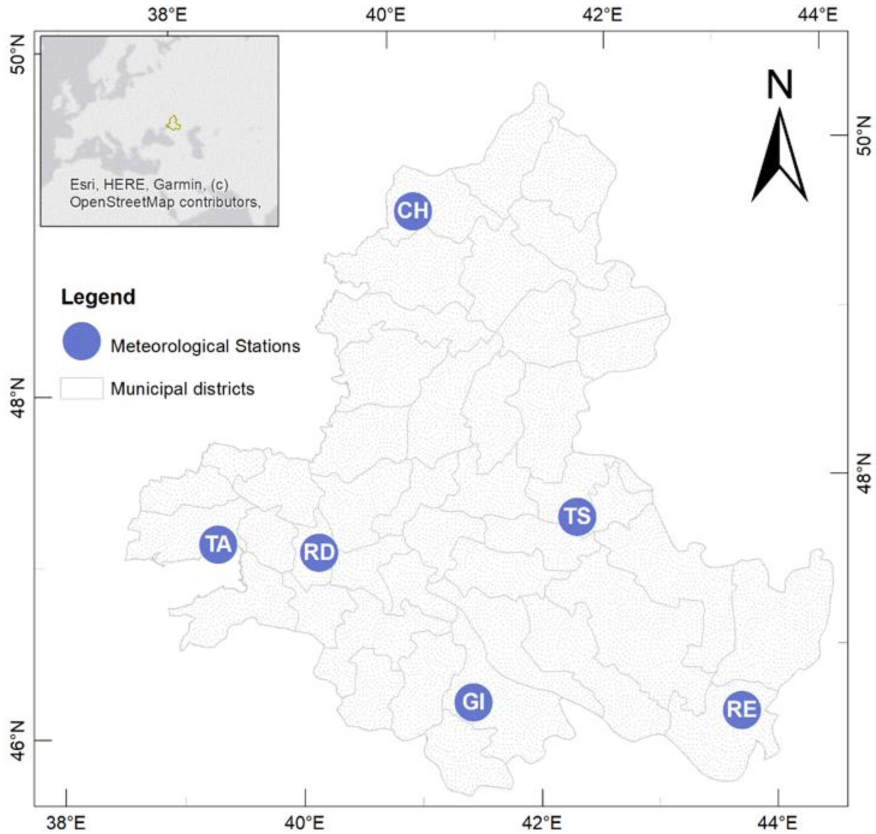

Figure 1. Study area and the meteorological stations considered

Given these factors, identifying trends and developing forecasting tools for drought events in the Rostov Region is an urgent research priority. Doing so would enable the development of timely response strategies to reduce the risk of agricultural losses. The present study aims to address this need by conducting a retrospective analysis of drought trends using multi-year precipitation data and by exploring the potential of the Seasonal Autoregressive Integrated Moving Average (SARIMA) approach to forecast fluctuations in the regional moisture regime.

Material and Methods

Precipitation dataset

This study utilized atmospheric precipitation (PR) data from six meteorological stations located in the Rostov Region, covering the period 1960–2024. These data were primarily obtained from the World Data Center of the Russian Research Institute of Hydrometeorological Information (RRIHI-WDS, 2025). Details of the selected meteorological stations are provided in Table 1 and illustrated in Figure 1.

To ensure data completeness, missing values in some stations were supplemented using records from the U.S. National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/cdo-web/). As a result, each time series achieved at least 95% completeness, in line with the recommendations of the World Meteorological Organization (WMO).

Table 1. List of meteorological stations, their WMO (World Meteorological Organization) number, latitude, longitude and altitude (m)

Station name*	WMO no.	Latitude (N)	Longitude (E)	Altitude (m)
Chertkovo (CH)	34432	49.23	40.10	136
Tsimlyansk (TS)	34646	47.38	42.07	66
Rostov-on-Don (RD)	34730	47.25	39.82	66
Taganrog (TA)	34720	47.20	38.95	30
Gigant (GI)	34740	46.52	41.35	79
Remontnoe (RE)	34759	46.34	43.40	106

* Meteorological stations are ordered from north to south

Methodological Framework

The methodological structure of the study comprises four main steps (Figure 2):

i. Retrospective analysis of drought events based on the distribution of SPI values from 1960 to 2024;
ii. Time series analysis of precipitation using the SARIMA model;
iii. Model diagnostics and selection, followed by precipitation modeling;
iv. Drought forecasting through SPI values calculated from SARIMA-modeled precipitation data.

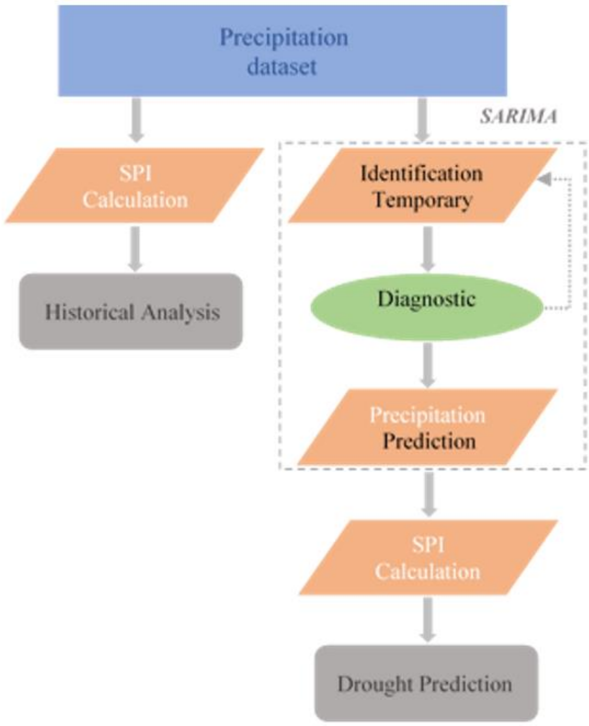

Figure 2. The framework for the proposed methodology

Standardized Precipitation Index (SPI)

The SPI is a standardized metric used to quantify precipitation anomalies over a specific time period (McKee et al., 1993). Since precipitation data rarely conform to a normal distribution, a gamma probability density function is fitted to the observed frequency distribution of monthly precipitation values. The resulting probabilities are then transformed into a standard normal distribution, yielding SPI values with a mean of zero and a standard deviation of one.

Positive SPI values reflect wetter-than-average conditions, whereas negative values indicate precipitation deficits. This standardization enables consistent assessment of drought and wet periods across different regions and time frames. Drought classification according to SPI thresholds is presented in Table 2.

Table 2. Drought classification according to SPI

SPI value	Drought classification
> 2.0	Extreme wet
from 1.50 to 1.99	Very wet
from 1.00 to 1.49	Moderately wet
from 0.99 to−0.99	Near normal
from −1.00 to −1.49	Moderately dry
from −1.50 to −1.99	Severely dry
< −2.0	Extremely dry

SPI calculation requires long-term precipitation data, with a minimum of 30 years recommended by the WMO. The index can be computed over various accumulation periods (e.g., 3, 6, 9, 12, and 24 months), each reflecting different hydrological and agricultural impacts (Panigrahi and Vidyarthi, 2024). Shorter periods (1–6 months) are relevant for assessing agricultural and soil moisture conditions, whereas longer periods (6–24 months) better capture impacts on river flows, groundwater levels, and reservoirs (Svoboda et al., 2012).

In this study, two SPI intervals were selected to assess drought during critical crop development stages in the Rostov Region (Gudko et al., 2021):

SPI-3 (May): representing moisture conditions from March to May, corresponding to the early vegetation phase;

SPI-6 (September): reflecting moisture availability during the entire active growing season from April to September.

Historical Analysis

Historical drought trends and moisture conditions in the Rostov Region were analyzed using SPI-3 and SPI-6 values over the 1960–2024 period. The Mann-Kendall test was employed to assess the presence of significant trends. Drought events were identified as years when SPI values were below −1.0. For temporal comparison, the dataset was divided into seven periods:

Period I (1960–1969), Period II (1970–1979), Period III (1980–1989), Period IV (1990–1999), Period V (2000–2009), Period VI (2010–2019), and Period VII (2020–2024).

Seasonal Autoregressive Integrated Moving Average (SARIMA)

The SARIMA model, an extension of the ARIMA framework, was applied to forecast precipitation at each meteorological station. Unlike standard ARIMA, SARIMA incorporates seasonal components to account for cyclical patterns in time series data. The model includes autoregressive terms (AR), differencing (to address non-stationarity), and moving average (MA) components, along with their seasonal counterparts (Ottom et al., 2023). Technical details on SARIMA implementation can be found in Huang and Petukhina (2022).

- To evaluate model performance, several statistical metrics were applied, including:
- Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) for absolute deviation;
- Mean Absolute Percentage Error (MAPE) for relative accuracy;
- Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) for model comparison and complexity control (Ding et al., 2017; Ray et al., 2021).

Forecasting was limited to a two-year horizon (2025–2026) due to the emergence of physically implausible precipitation values over longer intervals. In addition to statistical accuracy, the practical interpretability of forecasted values was also considered to ensure consistency with regional climatic norms. The resulting precipitation forecasts were used to compute SPI-3 and SPI-6 values for the same stations.

Spatial Distribution and Interpolation

To visualize spatial variability, SPI-3 and SPI-6 values derived from SARIMA-based forecasts were interpolated across the study area using kriging with a spherical variogram model in ArcGIS. Meteorological stations served as reference points. The resulting spatial distributions were classified according to the SPI categories shown in Table 2.

Results and Discussion

Historical Analysis

Dynamics of moisture conditions

The interannual dynamics of SPI-3 and SPI-6 values for the period 1960–2024 at the selected meteorological stations are presented in Figures 3 and 4. Overall, a weak positive trend in SPI-3 was observed across all stations, indicating a general improvement in moisture conditions during the early crop growth phase. Similar trends in SPI-6 were recorded at RE, TS, and CH stations, whereas at GI, RD, and TA stations, SPI-6 showed a slight, non-significant decrease.

The distribution of SPI-3 values suggests that normal moisture conditions prevailed during most of the study period. For example, normal conditions were recorded in 65% and 69% of years at GI and RE, and in 72%, 72%, and 75% of years at RD, TA, and TS, respectively. At CH station, normal moisture conditions were observed in 80% of the years, reflecting the most stable hydrological regime in the study area. Moisture surpluses during the early growing season (SPI-3 > 1) were observed in 17%, 15%, 11%, 9%, 14%, and 6% of years for GI, RE, RD, TA, TS, and CH stations, respectively. Notably, the majority of very wet and extremely wet conditions were recorded between 2010 and 2024.

Regarding SPI-6, normal moisture conditions during the full vegetation period were recorded in 60%, 66%, and 62% of years for GI, RD, and TS stations, respectively, while at other stations the proportion ranged between 72% and 74%. The highest moisture levels were mostly observed in the decade 1970–1979, during which SPI-6 values reached 1.96 at RE, 2.14 at RD, 1.84 at TA, 2.48 at TS, and 1.86 at CH—values corresponding to very moist or extremely moist conditions (Figure 4).

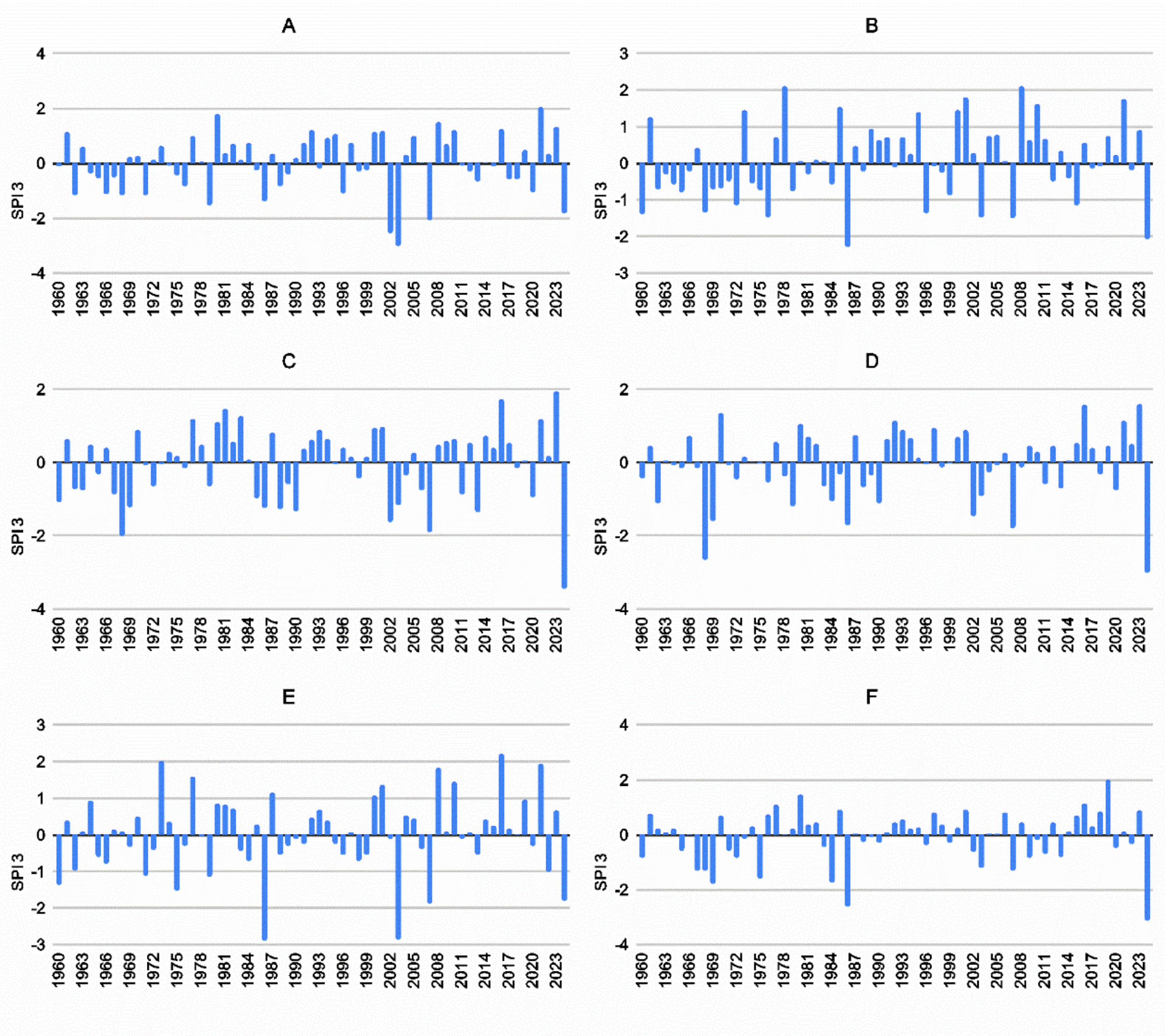

Figure 3. Dynamics of the SPI-3 indicator at the GI (A), RE (B), RD (C), TA (D), TS (E) and CH (F) meteorological stations in the period 1960–2024

The observed increase in SPI-3 values during the early growing season aligns with findings from other studies. In southern Russia, including Rostov Region, recent decades have seen a shift in precipitation from summer and autumn toward spring and winter months, contributing to more frequent years with normal or above-normal moisture availability (Ashabokov et al., 2018; Gudko et al., 2024).

Analysis of the frequency of dry events

The frequency of drought events in the period 1960–2024 in relation to ten-year intervals is presented in Tables 3 and 4. According to the SPI-3 value, in general, the driest conditions in the initial growing season in Rostov Region occurred in the periods 1960–1969 and 2000–2009. In the period 1960–1969, the greatest number of drought events was observed. At the same time, while at meteorological station GI during this period during three years moderate drought was observed in the initial period of vegetation, for example, for RD and TA single cases of severe or extreme drought were observed. The frequency of drought events at the beginning of the growing season was lower between 1970 and 1979 (Table 3). No years with extreme drought were observed, but isolated cases of severe drought were observed for weather stations GI, TS, and CH. At the same time, for TS during this period moisture conditions were twice characterized as moderately dry. The period 1980–1989 was comparable to the previous period in terms of the total number of drought events. However, for weather stations RE, TS and CH, years with extreme drought in the initial growing season were recorded (Table 3).

Sufficiently favorable conditions in the initial growing season were observed in the period 1990–1999. In this time period, only at weather stations GI, RE, RD and TA single cases of moderate drought were observed, and years with severe or extreme drought were not observed. The 2000–2009 period was characterized by an increase in the frequency of drought events of the initial growing season in the region. At the same time, a sharp increase in the frequency of extreme drought was observed. For meteorological station GI the number of such events in this period was repeated three times and a single case was recorded at TS. Cases of severe drought at the beginning of the growing season were observed in some years at some other weather stations, such as RD and TA (Table 3). During the period 2010–2019, the moisture conditions of the beginning of the growing season were the least drought conditions. According to the SPI-3 values obtained, the wetting conditions decreased only to the level of moderate drought and only for weather stations RE and RD.

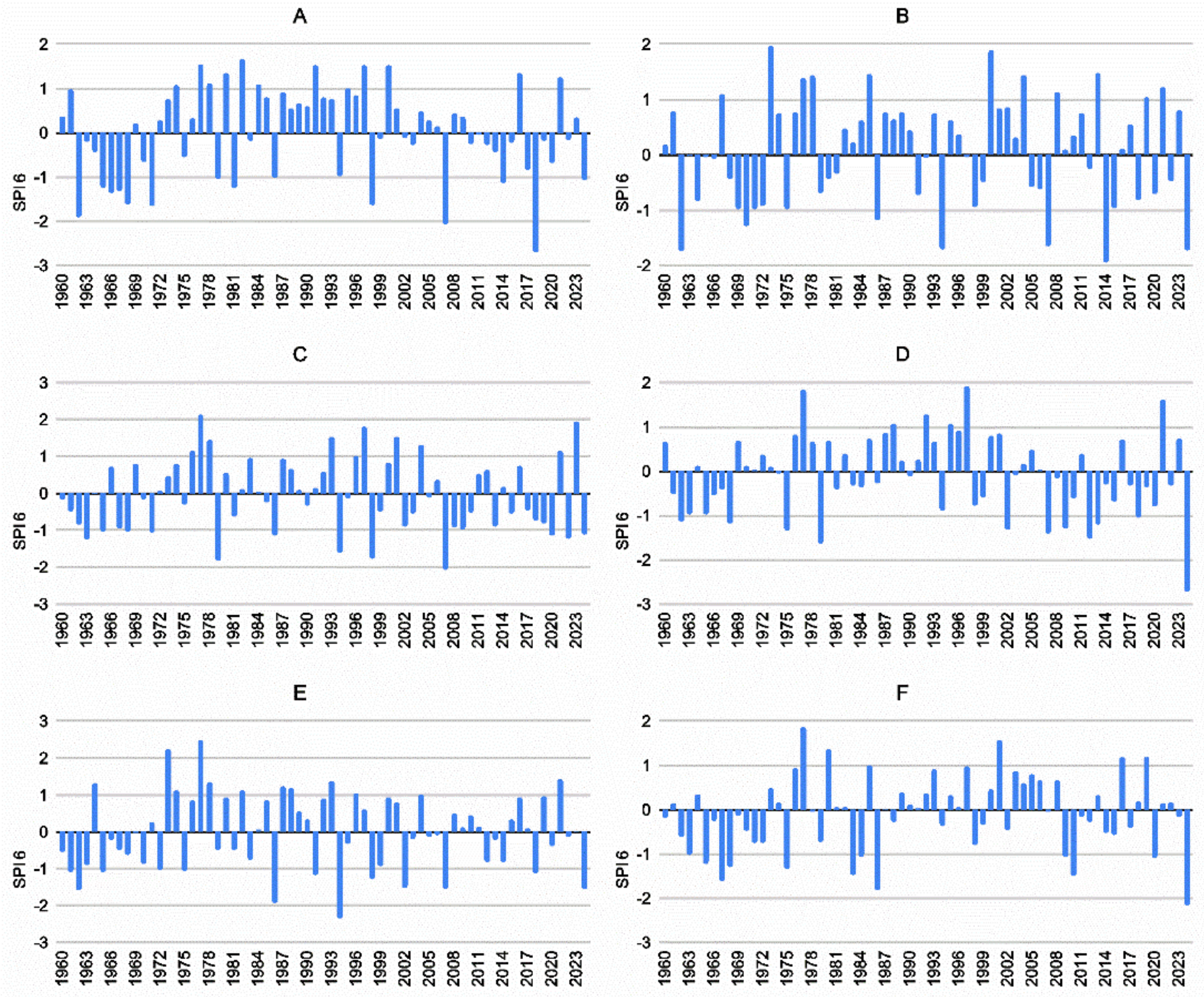

Figure 4. Dynamics of the SPI-6 indicator at the GI (A), RE (B), RD (C), TA (D), TS (E) and CH (F) meteorological stations in the period 1960–2024

In the five-year period 2020–2024, the number of drought events was quite high. However, the main years with drought in the initial period of crop vegetation in the Rostov region occurred in 2024, when extreme (RE, RD, TA, CH) or severe drought (GI, TS) was established throughout the region. It is worth noting that in 2024 for three weather stations at once, namely for RD, TA and CH, the absolute minimum SPI-3 for the entire observation history was noted, and its value amounted to -3.43, -3.01 and -3.1, respectively.

The frequency of drought events according to SPI-6 generally correlates with the frequency of SPI-3 (Table 4). Similarly, the period 1960–1969 had the highest cumulative number of drought events during the entire growing season (Table 4). No extreme drought events were identified during this period, but severe drought was observed for weather stations GI, RE, TS, and CH in some years (Table 4). Moderate drought in this ten-year period was observed for all meteorological stations except RE. However, for weather stations GI, RD and CH, moderate drought during the growing season was observed three times during the decade. The frequency of drought events throughout the growing season also showed a decrease in the following decade. Incidences of extreme drought during the period 1970–1979 were also not observed on SPI-6, but isolated occurrences of severe drought were observed on GI, RD, and TA. At the same time, moderately dry conditions were observed at all weather stations at least once.

Table 3. Number of years per decade with moderately dry (MD), severely dry (SD) and extremely dry (ED) conditions according to SPI-3 at the meteorological stations GI, RE, RD, TA, TS and CH during the period 1960–2024

Period/Meteorological stations		SPI-3		
		MD	SD	ED
1960–1969	GI	1962, 1966, 1968	-	-
	RE	1960, 1968	-	-
	RD	1960, 1969	-	1968
	TA	1962	1969	1968
	TS	1960	-	-
	CH	1967, 1968	1969	-
1970–1979	GI	1971	1979	-
	RE	1972, 1976	-	-
	RD	-	-	-
	TA	1979	-	-
	TS	1971, 1979	1975	-
	CH	-	1975	-
1980–1989	GI	1986	-	-
	RE	-	-	1986
	RD	1986, 1988	-	-
	TA	1984	1986	-
	TS	-	-	1986
	CH	-	1984	1986
1990–1999	GI	1996	-	-
	RE	1996	-	-
	RD	1990	-	-
	TA	1990	-	-
	TS	-	-	-
	CH	-	-	-
2000–2009	GI	-	-	2002, 2003, 2007
	RE	2003, 2007	-	-
	RD	2003	2002, 2007	-
	TA	2002	2007	-
	TS	-	2007	2003
	CH	2003, 2007	-	-
2010–2019	GI	-	-	-
	RE	2015	-	-
	RD	2013	-	-
	TA	-	-	-
	TS	-	-	-
	CH	-	-	-
2020–2024	GI	2020	2024	-
	RE	-	-	2024
	RD	-	-	2024
	TA	-	-	2024
	TS	2022	2024	-
	CH	-	-	2024

The number of drought events in the periods 1980–1989 and 1990–1999 during the growing season in the study region was comparable and quite low over the entire study period. However, in the period 1990–1999, a higher frequency of severe drought events was observed, and for the first time in the study period, extreme drought was observed at weather station TS. The period 2000–2009 was characterized by a further increase in the frequency of drought events, and especially extreme drought events. In this decade, such conditions during the growing season were established at meteorological stations GI and RD. Severe drought in 2000–2009 was also observed at weather stations RE and twice at TS. At the same time at TA for three years moisture conditions were characterized as moderately dry. The 2010–2019 period is also characterized by single occurrences of extreme (GI) and severe (RE and TA) drought. For the five-year period 2020–2024, drought events similarly occurred for the most part in 2024. In this year, moisture conditions during the growing season were characterized as extreme or severely dry for most weather stations.

Table 4. Number of years per decade with moderately dry (MD), severely dry (SD) and extremely dry (ED) conditions according to SPI-3 and SPI-6 at the meteorological stations GI, RE, RD, TA, TS and CH during the period 1960–2024

Period/Meteorological stations		SPI-3		
		MD	SD	ED
1960–1969	GI	1965, 1966, 1967	1962, 1968	-
	RE	-	1962	-
	RD	1963, 1965, 1968	-	-
	TA	1962, 1968	-	-
	TS	1961, 1965	1962	-
	CH	1963, 1965, 1968	1967	-
1970–1979	GI	1979	1971	-
	RE	1970	-	-
	RD	1971	1979	-
	TA	1975	1979	-
	TS	1972, 1975	-	-
	CH	1975	-	-
1980–1989	GI	1981, 1986	-	-
	RE	1986	-	-
	RD	1986	-	-
	TA	-	-	-
	TS	-	1986	-
	CH	1983, 1984	1986	-
1990–1999	GI	1996	-	-
	RE	1996	-	-
	RD	1990	-	-
	TA	1990	-	-
	TS	-	-	-
	CH	-	-	-
2000–2009	GI	-	-	2002, 2003, 2007
	RE	2003, 2007	-	-
	RD	2003	2002, 2007	-
	TA	2002	2007	-
	TS	-	2007	2003
	CH	2003, 2007	-	-
2010–2019	GI	-	-	-
	RE	2015	-	-
	RD	2013	-	-
	TA	-	-	-
	TS	-	-	-
	CH	-	-	-
2020–2024	GI	2020	2024	-
	RE	-	-	2024
	RD	-	-	2024
	TA	-	-	2024
	TS	2022	2024	-
	CH	-	-	2024

Note that the analysis of SPI time series in the monthly approximation for a similar list of meteorological stations in Rostov Region was studied earlier in (Salmin et al., 2021). For the thirty-year period 1990–2020, the authors found negative trends of monthly SPI in the dynamics of interannual variability. The period 2010–2020, according to the authors, turned out to be a drought period, which partially agrees with the results of our study in terms of SPI-6. At the same time, as in our study, the highest moisture content and a fairly high number of extreme droughts were observed in the period 2000–2009 (Salmin et al., 2021).

Forecast of moisture conditions

SARIMA model indicators and forecasting horizon

For each station, the optimal SARIMA configuration was selected based on the lowest values of the Akaike Information Criterion (AIC) and minimum error metrics (RMSE, MAE, MAPE) calculated on the validation datasets. Individual sets of model parameters (p, d, q) and (P, D, Q) with seasonal components were defined for each location to ensure the best fit to historical precipitation data and the stability of forecasts.

The forecast was limited to the next two years (2025-2026) because a longer horizon would lead to physically unrealistic precipitation values (e.g., negative) and a significant deviation from the climatic norm. The criteria for selecting such a horizon were: i) reliability of the forecast within the available historical data, ii) absence of anomalies beyond reasonable interpretation of precipitation, and iii) preservation of model stability when seasonal variations are taken into account within the limits of reasonable extrapolation.

Forecasting of dry events

Forecast distribution of SPI-3 and SPI-6 values on the territory of Rostov region, calculated on the basis of modeled precipitation data, are presented in Figures 5 and 6, respectively. According to the obtained models, moisture conditions in the initial growing season according to SPI-3 (March-May) in 2025 in most of the region will correspond to the norm. Drought events are not predicted during this period (Figure 5). As one moves westward into the RD, TA, and CH weather station area, moisture conditions will change to very to extremely wet. In 2026, moderately dry conditions will cover a small portion of the region in the eastern part of the region. At the same time, the isoline from extreme wetness will shift to the east.

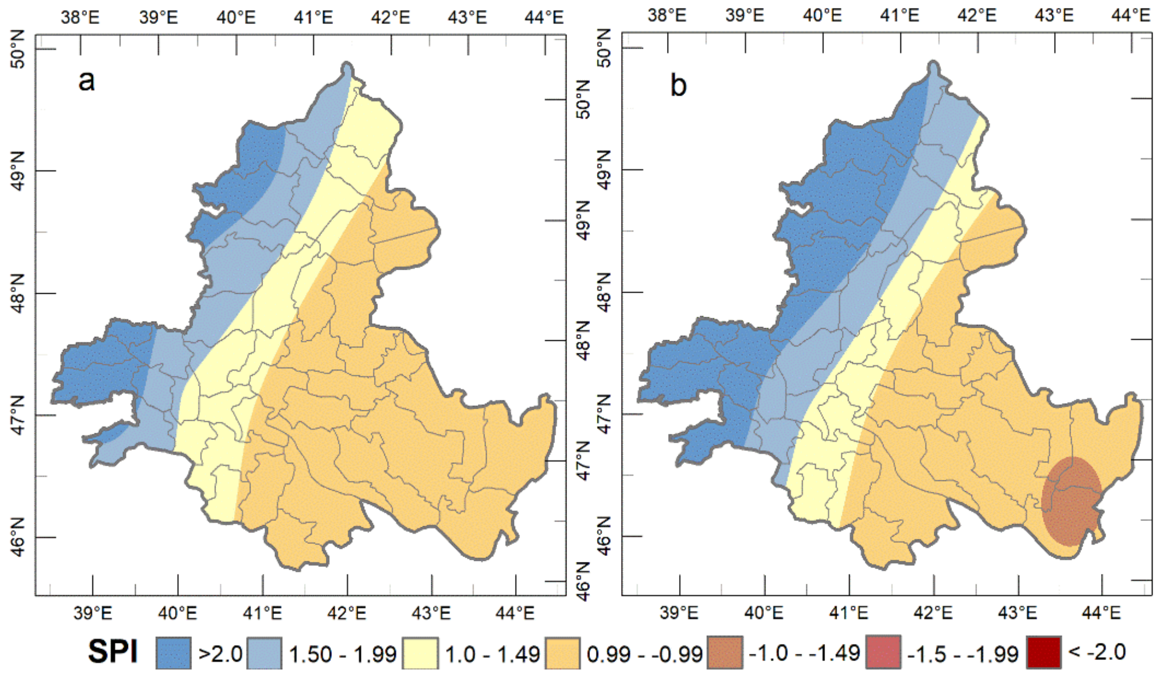

Figure 5. Forecast of the distribution of the SPI-3 (March-May) indicator in the Rostov region for 2025 (a) and 2026 (b)

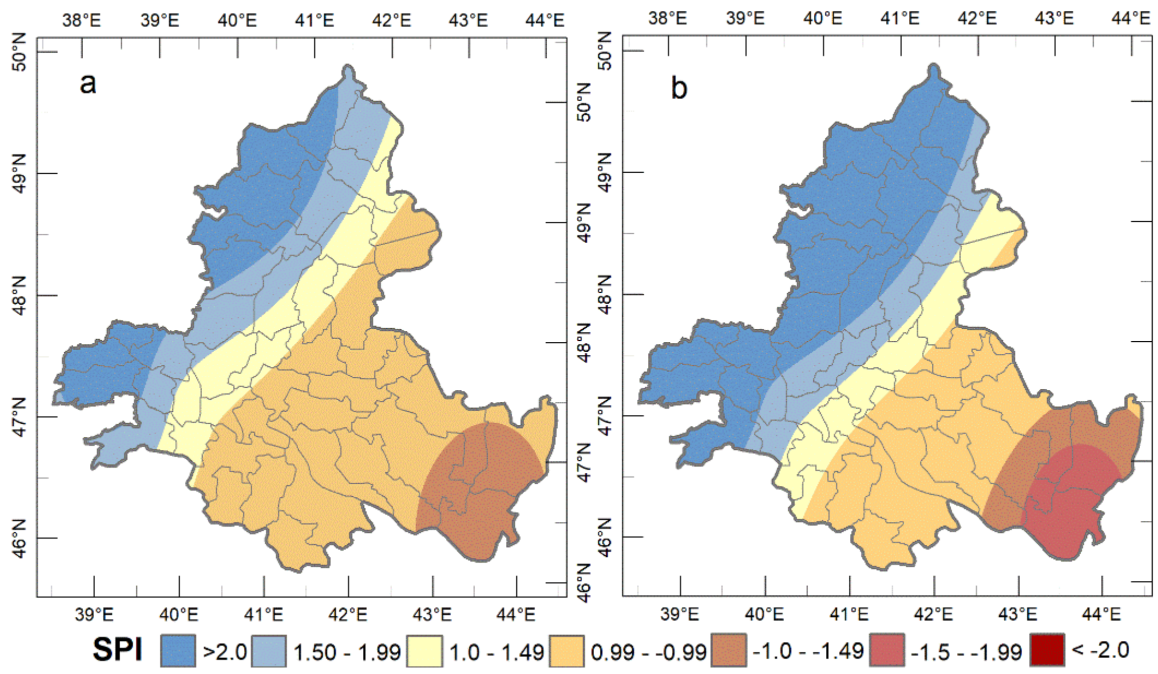

Figure 6. Forecast of the distribution of the SPI-6 (April-September) indicator in the Rostov region for 2025 (a) and 2026 (b)

According to the obtained models, moisture conditions during the entire period of active vegetation of crops according to SPI-6 (April - September) in 2025 in most of the region will also correspond to the norm (Figure 6). However, moderate drought conditions are forecast in the eastern part of the region during this period. Extremely wet conditions are characterized in the areas where the TA and CH weather stations are located. In 2026, according to SPI-6 model data, the eastern part of the Rostov region is characterized by an intensification of moisture deficit to severe drought, as well as a slight expansion of the territory covered by moderate drought. At the same time, the isoline with extreme and very wet conditions will also shift quite significantly to the east of the Rostov Region.

Conclusion

The application of SPI-3 and SPI-6 in this study enabled a comprehensive analysis of drought dynamics in the Rostov Region during two critical phases of crop development: the early vegetation period (March–May) and the full active growing season (April–September). The findings revealed that the highest frequency of drought events for both periods occurred during the initial decade (1960–1969). In the subsequent decades, the frequency of droughts generally declined, particularly during the full growing season, and remained relatively stable across the last three ten-year intervals. However, for the early vegetation period, fluctuations were more pronounced, with periods of low drought frequency followed by intervals marked by more frequent drought occurrences.

Although the overall trend pointed to a slight increase in moisture availability—especially during the early season—this has not entirely mitigated the region's vulnerability. Of particular concern is the observed rise in the frequency of extreme drought events, which pose significant risks to agricultural productivity. This trend is likely to intensify under ongoing climate change conditions and calls for continued monitoring and adaptive planning.

The SARIMA modeling approach used in this study highlighted both the potential and limitations of time series forecasting for precipitation. While the method proved useful for short-term projections, its predictive capacity diminished over longer horizons due to deviations from climatic norms and the emergence of physically implausible values. For this reason, the forecast horizon was restricted to two years. Despite these limitations, SARIMA can serve as a valuable supplementary tool for forecasting precipitation trends and drought conditions.

The methodological framework presented in this study can be readily adapted for use in other regions facing similar climatic challenges, contributing to a broader understanding of drought dynamics and supporting the development of mitigation strategies in agricultural systems.

Acknowledgement

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Comparative effects of poultry and cow dung-based composts on soil pH, organic matter, and macronutrient dynamics in a tropical sandy loam

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Abstract

Luxuriant crop development, especially in leafy vegetables, is strongly influenced by soil pH, organic matter, and macronutrients (N, P, K, Ca, and Mg). However, tropical soils are often deficient in these fertility indicators due to repeated cultivation without proper soil management or restoration. To maintain adequate organic matter content and improve soil nutrient status, research into organic soil fertility restoration strategies has become essential, particularly since inorganic fertilizers are often expensive, scarce, hazardous, and environmentally unfriendly. Cow dung/sawdust (CDS) and poultry dung/sawdust (PDS) have been the primary composting materials used. Therefore, this study aimed to investigate the effects of CDS and PDS composting on their chemical properties, as well as their impact on selected soil chemical properties. The compost mixtures were separately prepared and composted for 22 weeks at an ambient temperature of 24°C. Temperature changes were recorded fortnightly before watering. Samples from the compost heaps were chemically analyzed at the second and twenty-second weeks. Subsequently, the composts were incubated with soil at a rate of 30 t/ha for 16 weeks under room temperature. Soil pH, organic matter, and macronutrients (N, P, K, Ca, and Mg) were evaluated at 4, 8, 12, and 16 weeks of incubation. Temperature profiles showed higher readings in the CDS heap, suggesting faster composting. At 22 weeks, both composts showed improved chemical properties, with CDS recording higher values across most parameters. During incubation, soil pH, organic matter, N, P, and K increased steadily, indicating ongoing mineralization, whereas Ca and Mg contents declined. Both composts demonstrated potential to increase soil pH, organic matter, and macronutrient levels. However, PDS-treated soils showed greater mineralization of organic matter and macronutrients, making poultry dung/sawdust compost more effective for soil maintenance, fertility restoration, and sustainable crop production.

Keywords: Composts, macro nutrients, management techniques, organic matter, soil fertility restoration.

Introduction

Soil pH and macronutrients are important indicators of soil fertility (MohammedZein et al., 2023). Adequate levels of macronutrients are required for crops to complete their life cycle without interruption. A deficiency or absence of any of these essential elements can hinder crop development and even lead to plant mortality. Unfortunately, most tropical soils lack these critical fertility components, thereby necessitating appropriate soil maintenance, restoration, and management practices (Amer, 2019). Sustainable soil management enhances agricultural productivity, improves environmental conditions, and promotes overall soil health. A healthy soil is characterized by balanced nutrient availability, high humus content, and a diverse population of soil organisms. The primary cause of declining soil fertility in tropical regions is the continuous removal of nutrients through crop harvest without sufficient replenishment (Isitekhale and Osemwota, 2010). This

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situation has led to the increasing use of both organic and inorganic external inputs to restore nutrient balance and sustain productivity.

In Nigeria, the use of inorganic fertilizers has become a common strategy to offset the negative nutrient budgets in crop production systems (Kekong et al., 2010). While these fertilizers can significantly increase crop yields depending on management practices and environmental conditions, they are often expensive, difficult to obtain, and unaffordable for smallholder farmers (Tesfaye et al., 2011). As a result, researchers have shifted their focus to promoting organic fertilizers that are inexpensive and locally available. Improved crop production practices now emphasize nutrient management through the use of organic fertilizers, which have shown more beneficial effects on tropical soils compared to synthetic nutrient sources. Consequently, organic farming practices that rely on natural nutrient cycles are increasingly being encouraged (Amgai et al., 2018).

The numerous documented benefits of organic wastes on soil properties and productivity have contributed to the growing acceptance and application of composts (Omolayo et al., 2011; Fawole, 2015; Adeyemi, 2025). While mineral fertilizers may initially boost yields, they can eventually lead to soil acidification and nutrient imbalance. In contrast, composts enhance the chemical, physical, and biological properties of soils by increasing organic matter and fostering greater microbial diversity and activity (Amgai et al., 2018). Additionally, using organic wastes from farms and animal industries helps mitigate environmental hazards by converting waste into valuable soil amendments (Adeleye and Ayeni, 2010). In Nigeria, compost materials such as poultry and cattle dung are abundant, making composting a practical and increasingly preferred method among farmers.

Compost also acts as a natural pesticide, soil conditioner, and a rich source of humus and humic acids. Research shows that adding organic matter to soil increases microbial populations, which in turn helps suppress root diseases (Talat et al., 2020). Microorganisms in compost produce esters that enhance soil aggregation, creating a friable and well-structured texture (Chotte, 2005). Compost is a porous, moisture-retentive medium that holds soluble nutrients and provides support for healthy plant growth. When applied directly to soil or growing media, compost enhances organic matter content and improves fertility. Regular application leads to long-term productivity and sustainability in crop and vegetable production. Thus, compost is a reliable means of maintaining long-term soil fertility while reducing the need for synthetic fertilizers.

Cattle dung consists of fibrous and liquid materials derived from the digestive tract of the animal, including substances such as cellulose, lignin, hemicellulose, urea, and various minerals. This makes it a nutrient-rich, environmentally sustainable input for enhancing crop production. It can be used as an alternative to synthetic fertilizers. However, if not incorporated into the soil by earthworms or dung beetles, cow dung can dry on the surface, negatively affecting grazing (Thomas, 2020). Cattle manure improves soil structure, organic matter content, water infiltration, and tilth (Bakayoko et al., 2009; Mosebi et al., 2015; Rayne and Aula, 2020). Although the benefits may not be immediate, long-term application leads to enhanced yields and soil quality (Reddy et al., 2000). The nutrient value of cattle manure varies based on factors such as animal type, diet, storage, and handling. Composting manure stabilizes nutrients, reduces volume, minimizes odor, and eliminates weed seeds and pathogens (Zublena et al., 1986). Therefore, composted cattle manure is considered more effective than fresh manure for agricultural use (Kekong et al., 2010; Fawole et al., 2019, 2021; Adeyemi, 2024, 2025).

Poultry manure is considered the most nutrient-rich among livestock manures, containing significant amounts of N, P, K, and Ca (Mitchell and Donald, 1999). It serves as a concentrated source of readily available nutrients for soil improvement and crop production (Azad et al., 2022). Poultry manure can be applied directly to fields without composting, making it convenient for farmers (Prabu, 2009; Adeyemi et al., 2021). However, its composition varies based on poultry species, feed, litter type, and handling methods (Zublena et al., 2012). Nitrogen in poultry manure is mainly in the form of uric acid, which can convert to ammonia and be lost through volatilization if improperly stored. As the manure mineralizes, the nitrogen becomes available to plants, with mineralization rates ranging from 40–90% depending on conditions (Mitchell and Donald, 1999). Poultry manure is used at various stages—before planting, during sowing, and as a top dressing (Adeyemi et al., 2021). Like cattle manure, it can either supplement or replace commercial fertilizers, and it has been used both alone and in combination with other materials (Omolayo et al., 2011; Fawole, 2015; Adeyemi et al., 2021; Fawole et al., 2019, 2021).

Sawdust, a carbon-rich organic material, is produced as a byproduct of wood processing in sawmills and carpentry workshops. Although it contains little in the way of nutrients essential for microbial activity, its high lignin, cellulose, and pectin content makes it suitable for composting. Nitrogen must be available for microbial decomposition of sawdust to occur (Rudiger et al., 2018). Initially, microbes may immobilize nitrogen, limiting plant uptake. However, once decomposition is complete, nutrients become available to crops. Sawdust is widely used as mulch, litter, or soil amendment, and its high moisture-absorbing capacity supports the composting process by balancing the carbon-to-nitrogen ratio (Rhoades, 2022). Sawdust from all tree types can be used, though material from chemically treated wood should be pre-soaked to remove harmful substances. When used in appropriate amounts, sawdust helps create favorable conditions for compost maturation (Qasim et al., 2018).

Cow dung and poultry manure are widely used in composting, often in combination with sawdust as a carbon source (Fawole et al., 2019, 2021). In Nigeria, large amounts of organic waste are generated and often discarded improperly, posing environmental risks. Composting is a sustainable solution for converting these wastes into nutrient-rich inputs for crop production (Adeleye and Ayeni, 2010). It facilitates the breakdown of organic matter by soil organisms and helps restore humus and essential nutrients (Loughrey, 2024).

Soil productivity in tropical systems depends heavily on pH, organic matter, and macronutrient availability. However, due to ongoing cultivation and poor management, these fertility indicators are frequently depleted. Organic nutrient sources have emerged as viable alternatives to inorganic fertilizers, which are costly, scarce, and environmentally hazardous (Adeyemi and Omotoso, 2023; Adeyemi, 2024). Meanwhile, organic farm wastes are often discarded unsustainably. When managed properly, these wastes can support soil fertility and crop productivity (Adeyemi, 2022). In Nigeria, cow dung–sawdust (CDS) and poultry dung–sawdust (PDS) composts are commonly used. Therefore, this study aimed to compare the effects of composting on the chemical properties of CDS and PDS, and to evaluate their respective impacts on soil pH, organic matter, and macronutrients (N, P, K, Ca, Mg) over time. The findings will inform sustainable soil management strategies and provide evidence-based recommendations for compost use in agricultural systems.

Material and Methods

Experimental site

The research was conducted at the Teaching and Research Farm of Ekiti State University, located along Iworoko-Ekiti Road, Ado-Ekiti, Nigeria. The site lies between latitudes 7°15′ and 8°5′ N and longitudes 4°45′ and 5°13′ E, within the rainforest zone of southwestern Nigeria. The average annual temperatures for February and March—the presumed hottest months—are 28 °C and 27 °C, respectively. Average daily sunshine is approximately 5 hours, with a mean annual solar radiation of 130 kcal/cm^2/year.

Chemical analysis of organic wastes

The organic wastes were air-dried, milled, and chemically analyzed. The pH of each sample was determined electrometrically in a 1:2 (w/v) sample-to-water ratio (IITA, 1982). Organic carbon content was measured using the dry ashing method (Nelson and Sommers, 1996), and total nitrogen was assessed by the micro-Kjeldahl method (Bremner, 1996). Samples were digested using a perchloric-nitric acid mixture, and phosphorus was determined using the vanadomolybdate yellow color method (Olsen and Dean, 1965). Potassium and sodium were measured with a flame photometer, while calcium, magnesium, manganese, iron, zinc, copper, and lead were quantified using atomic absorption spectrophotometry (AAS).

Experiment 1: Composting Effects on Compost Properties

The heap method was employed for composting. Cattle dung mixed with sawdust (CD + S) and poultry dung mixed with sawdust (PD + S) at a 1:1 ratio were heaped separately. Each heap measured 1.5 m in width and 1 m in height. The heaps were turned fortnightly to ensure aeration, and equal amounts of water were added to maintain moisture. Ambient and internal heap temperatures were recorded prior to each watering and turning. Temperature trends during the composting period were analyzed descriptively. Samples were collected at weeks 2 and 22—when heap temperatures had stabilized and composts had darkened, indicating maturity. These samples were analyzed for non-synthetic carbon, nitrogen, phosphorus, calcium, magnesium, potassium, sodium, manganese, iron, zinc, copper, and lead. The analytical methods used were the same as described above (Olsen and Dean, 1965; Nelson and Sommers, 1996; Bremner, 1996).

Determination of Soil Properties at the Study Site

Surface soils (0–15 cm) were randomly collected from the Teaching and Research Farm. The samples were air-dried, sieved (2 mm), and analyzed for particle size distribution, pH, total nitrogen, organic matter, available phosphorus, potassium, sodium, calcium, and magnesium. Particle size was determined by the hydrometer method (Sheldrick and Hand Wang, 1993), and pH was measured in a 1:2 soil-to-water ratio using the electrometric method (IITA, 1982). Total nitrogen was estimated using the macro-Kjeldahl digestion method (Bremner, 1996), while organic matter was determined by wet oxidation (Nelson and Sommers, 1996). Available phosphorus was analyzed using Bray's method (IITA, 1982). Exchangeable cations (K, Ca, Mg, Na) were extracted with 1 N NH_4OAc (Hendershot and Lalande, 1993). Potassium and sodium were quantified using a flame photometer, while calcium and magnesium were measured with AAS. Effective acidity was extracted using 1 N KCl and titrated with 0.05 N NaOH using phenolphthalein as an indicator (Thomas, 1982). The sum of exchangeable bases and acidity was used to calculate the effective cation exchange capacity (ECEC).

Experiment 2: Dynamics of soil reaction (pH), organic matter, N, P, K, Ca and Mg in composts-treated soils through Incubation Studies

Two (2) kilogrammes (kg) samples of soils from the study site were weighed into pots. Each enriched compost was used; by properly mixing with the soils at 30 t/ha. Properly mixed substances were dampened, covered and stored in a cool environment. Thorough mixing of pots' contents was done at weeks 4, 8, 12 and 16 of incubation and thereafter, total N, accessible phosphorus and inter-exchangeable potassium, calcium and magnesium, contained in sampled soils from the pots were measured. Each treated soil was replicated four times, making a total of 12 pots, arranged in a complete randomized design (CRD). The macro-Kjeldahl method was adopted for N determination, while the Bray P-1 method was involved in available P calculation and exchangeable K quantified by flame photometer after extraction with neutral normal NH_4OAc, while Ca and Mg contained in filtrates were quantified with atomic absorption spectrophotometer. Data generated were analyzed with anova, at 5%, and were described with charts.

Results

The chemical properties of the organic wastes

Table 1 shows the chemical properties of the compost materials i.e. the organic wastes used in the study. The compost materials (poultry droppings, cow dung and sawdust) had pH values of 8.4, 8.0 and 8.4 respectively. The poultry droppings gave the highest N (79.2 g/kg) value, followed by cow dung (53.9 g/kg N) while the least value was in saw dust, which contained 1.5 g/kg of N. Total P in cow dung was 26.8 g/kg while the other two compost materials-poultry manure and sawdust contained 8.6 and 0.2 g/kg P respectively. The Ca content of poultry manure (13.1 g/kg) was the highest amongst the organic wastes and followed by saw dust with 10.4 g/kg while cow dung gave the least value (9.5 g/kg). Total Mg was highest in poultry droppings (6.7 g/kg) followed by sawdust (6.4 g/kg) which was slightly higher than cow dung (6.0 g/kg). Total K was 5.2, 4.8 and 4.4 g/kg for poultry droppings, cow dung and saw dust respectively while Na content was 0.8 g/kg for cow dung and poultry droppings and 0.5 g/kg for sawdust. Poultry droppings contained 0.3 g/kg Mn while the content in cow dung and sawdust was the same at 0.2 g/kg. The Fe content was the same for cow dung and poultry droppings (0.5 g/kg) but 0.3 g/kg in sawdust. The Zn content was higher in cow dung (0.2 g/kg) than in poultry droppings and saw dust with 0.1 g/kg. The Cu values ranged from 0.03 to 0.1 g/kg while Pb was below detectable levels in the compost materials.

Table 1. Nutrient composition of compost materials

Parameters	Cow dung	Poultry dung	Sawdust
pH (H_2O)	8.0	8.4	8.4
Total N (g/kg)	53.9	79.2	0.9
Organic C (g/kg)	222.9	327.2	334.3
Total P (g/kg)	26.8	8.6	0.2
Calcium (g/kg)	9.5	13.1	10.4
Magnesium (g/kg)	6.0	6.7	6.4
Potassium (g/kg)	4.4	5.2	4.8
Sodium (g/kg)	0.8	0.8	0.5
Manganese (g/kg)	0.2	0.3	0.2
Iron (g/kg)	0.5	0.5	0.3
Zinc (g/kg)	0.2	0.1	0.1
Copper (g/kg)	0.1	0.03	0.03
Lead (g/kg)	ND	ND	ND

Physical and chemical characteristics of composts as affected by weeks of composting

Figure 1 shows the trend of changes in temperature during composting. The two main temperature ranges: mesophilic with optimum growth temperature range of between 20-45°C and thermophilic with optimum growth temperature range of between 50-70°C, often encountered in aerobic composting, were observed. At the first turning (2 weeks into composting), the temperature was 40 and 42°C which increased to 53 and 56°C for PDS and CDS respectively at the second turning (4 weeks into composting). At the third turning (6 weeks into composting), the temperatures of the materials increased to 62 and 66°C but decreased to 58 and 56°C for PDS and CDS respectively at 8 weeks and to 50°C for both heaps at 10 weeks. The decrease in temperature continued till 42 and 40°C at 12 weeks, 30°C at 14 weeks and to 24°C for PDS and 25°C for CDS at 16 weeks into composting. At 18 weeks, the temperature remained constant at 24 and 25°C in the PDS and CDS heaps respectively. At 20 weeks, the temperature on both heaps was observed to remain at 24°C and turning no longer reheated the piles; an indication that the piles have attained the curing stage. The temperatures for the heaps remained constant till 22 weeks. The composts had become brown/black in colour. These all indicate the maturity of the composts.

The chemical properties of compost samples taken at 2 and 22 weeks are shown in Table 2. At 2 weeks into composting, the pH values in the two composts were 8.0, for PDS and 8.3, for CDS; an indication that the two composts were basic. The values obtained for Total N, organic carbon and all the exchangeable cations were higher in the CDS based composts at 2 weeks into composting while total P was higher in PDS. The Pb content of the two composts was not detectable.

At 22 weeks into composting (Table 2), the pH of the two composts increased becoming more basic with pH values 8.2 for PDS and 8.4 for CDS. Also, there was an increase in total N, organic carbon, total P and exchangeable cations of the two composts except in Fe, where a reduction in the initially recorded values was observed. The particles had reduced in size and became consistent and soil-like in texture. It was also observed that the C: N for both compost samples got reduced at 22 weeks into composting.

Table 2. Chemical properties of the composts at 2 and 22 weeks into composting

Parameters	PDS		CDS	
	2 weeks	22 weeks	2 weeks	22 weeks
pH (H_2O)	8.0	8.2	8.3	8.4
Total N (g/kg)	3.91	4.22	6.02	6.40
Organic C (g/kg)	161.2	158.0	249.0	243.0
Total P (g/kg)	19.7	23.0	5.5	10.0
Calcium (g/kg)	9.0	11.5	11.2	13.0
Magnesium (g/kg)	5.3	6.2	6.3	6.8
Potassium (g/kg)	4.2	5.4	5.0	6.1
Sodium (g/kg)	0.04	0.04	0.11	0.13
Manganese (g/kg)	0.2	0.3	0.3	0.4
Iron (g/kg)	0.3	0.2	0.5	0.4
Zinc (g/kg)	0.2	0.3	0.2	0.5
Copper (g/kg)	0.1	0.2	0.1	0.3
Lead (g/kg)	ND	ND	ND	ND

Chemical properties and particle size distribution of soils used for incubation

The properties of the soil used for the incubation studies are shown in Table 3. The soil was a slightly acidic (pH 5.8 in KCl and 6.6 in water) sandy loam with organic matter content at 14.6 g/kg. Total N in soil was 0.8 g/kg; available P was 13.0 mg/kg while the exchangeable cations; K, Ca, Mg and Na were 0.3, 7.0, 1.8 and 0.1 cmol/kg respectively.

Table 3. Chemical properties and particle size distribution of experimental soils

Parameters	Values
pH (1:1 KCl)	5.8
pH (H_2O)	6.6
Total Nitrogen (g/kg)	0.8
Organic matter (g/kg)	14.6
Available P (mg/kg)	13.0
Exchangeable cations	
Calcium (cmol/kg)	2.8
Magnesium (cmol/kg)	1.8
Potassium (cmol/kg)	0.3
Sodium (cmol/kg)	0.1
Exchangeable Acidity	0.6
ECEC	5.6
Base saturation (g/kg)	893.0
Particle Size Analysis	
Sand (g/kg)	799.0
Silt (g/kg)	132.0
Clay (g/kg)	69.0
Textural Class (USDA)	Loamy sand

Dynamics of soil reaction (pH), organic matter, N, P, K, Ca and Mg in composts-treated soils through Incubation Studies.

Effects of PDS and CDS on soil reaction (pH)

Figure 2 shows the pH values of the composts-treated soils obtained during incubation study. The experimental soil was slightly acidic, having great impact on the soil reaction values of the treated soils. The pH values of samples reduced through week 12 of soil incubation. The trend of soil pH reduction was similar, for all treatments in the treated, soils. However, soil acidity reduced after 12 weeks of incubation, as the pH values of all treated soils, including the control (soil alone) increased at 16 weeks of incubation. Though there were no significant differences among the treatments, but CDS treated soils gave the lowest pH values. The pH at 16 weeks of incubation ranged from 5.9 (CDS), through 6.0 (control) to 6.05 (PDS).

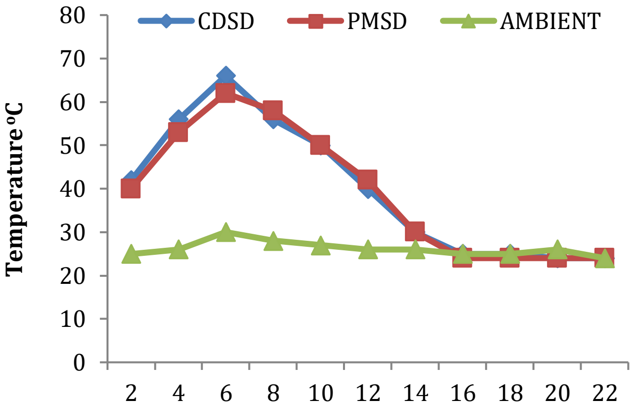

Figure 1. Temperature changes during composting

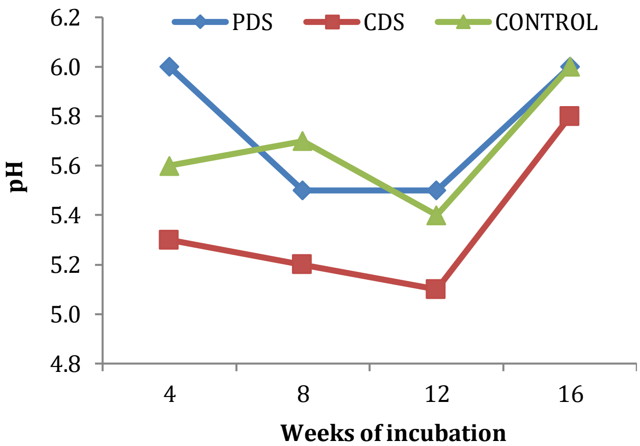

Figure 2. pH of the composts-treated soils obtained during incubation study

Effects of PDS and CDS on soil organic matter (SOM)

Soil organic matter (SOM) dynamics, as recorded from this study (Figure 3), showed that SOM at in the control (4.35 g/kg) was the highest at week 4, and it was significantly different from the least SOM value (2.65 g/kg), which was recorded from soils treated with PDS. The SOM recorded from soils treated with CDS (3.81 g/kg), also differed significantly from SOM value for PDS-treated soils. The organic matter contents of the treated soils decreased at week 8, with the control still having the highest SOM content (2.34 g/kg), followed by PDS (2.22 g/kg) and PDS giving the least SOM content (1.8 g//kg). However, there were no significant differences among the values obtained for the treated soils. There were no significant differences in the values of SOM recorded for the treatments at 12 weeks of incubation, but the CDS treated soils gave the highest SOM value (1.84 g/kg), followed by the control (1.75 g/kg). The PDS-treated soil gave the lowest SOM value of 1.61 g/kg. The SOM values (g/kg) recorded for the treatments at 16 weeks of incubation were in the order: PDS (2.8)> Control (2.3)> CDS (1.8). The PDS gave a SOM value significantly different from the CDS which gave the lowest SOM value.

Effects of PDS and CDS on total N in soil

Total N contents of the treated soils were greatly influenced by the addition of composts (Figure 4). Both compost types were effective in soil N enrichment, as N values recorded for soils treated with the two composts were significantly higher than N values in the control soil. The N values (g/kg) at 4 weeks of incubation were: 5.1, 4.1 and 0.6, recorded for PDS, CDS and control, respectively. Nitrogen dynamics in the treated soils followed the same pattern as in the SOM contents, as a reduction in N values was recorded at 8 weeks of incubation. There were no significant differences in the N values recorded from CDS and PDS-treated soil through the period of incubation. However, PDS has the highest values of N at all weeks in the incubation studies and the highest N overall (5.1 g/kg) at 4 and 16 weeks of incubation. Total N increased from 8 weeks into incubation, all through the 16 weeks of incubation.

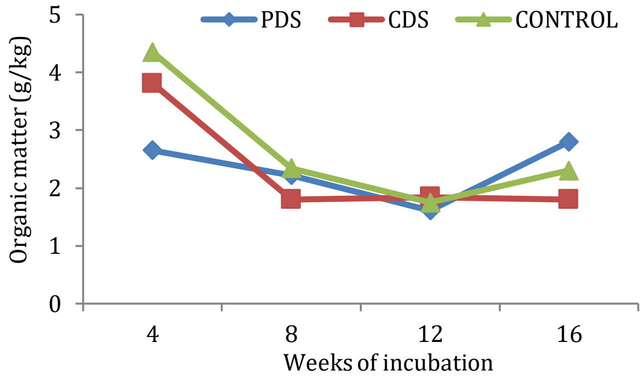

Figure 3. Organic matter contents (g/kg) values of the composts-treated soils obtained during incubation study

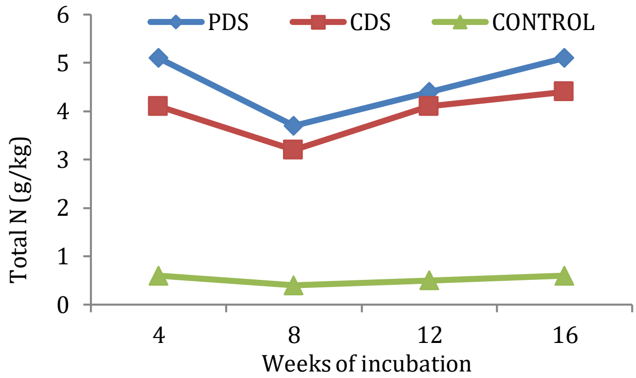

Figure 4. Total N contents (g/kg) of the composts-treated soils obtained during incubation study

Effects of PDS and CDS on soil available P

Though CD gave higher P value of 26.8 g/kg than 8.6 g/kg given by PD in their nutrient compositions analysis, the analysis of the resultant composts indicated that the available P content of PDS at 22 weeks into composting (23.0 g/kg) became higher than the available P content of CDS (10.0 g/kg). From the study, available P values obtained from the organically-treated soils significantly differed from the control soils (Figure 5). The PDS- treated soils gave the highest available P value (9.1 mg/kg) at 4 weeks of incubation, though not significantly different from the CDS-treated soils (8.4 mg/kg). Soils treated with CDS had continuous increase in available P all through the period of incubation, while a slight decrease was observed in PDS at 8 weeks of incubation (Figure 5). The PDS-treated soils also had the highest available P value (16.8 mg/kg) at 12 weeks of incubation and it differed significantly from the available P content of the CDS-treated soils (12.4 mg/kg). The highest available P value overall (19.0 mg/kg), was recorded from CDS at 16 weeks, though not significantly different from the available P value obtained from the PDS-treated soils (18.5 mg/kg). The lowest available P value was recorded from Control at 8 weeks of incubation (2.1 mg/kg). However, available P quantities of soils treated with CDS and PDS were greatly increased.

Effects of PDS and CDS on exchangeable K contents of the treated soils

The exchangeable K contents in soils treated with both composts increased continuously through the weeks of incubation (Figure 6). Up to 400% increase was recorded in the exchangeable K contents of treated soils compared to the exchangeable K contents of the control samples. The highest exchangeable K value at 4 weeks (0.47 cmol/kg) was recorded from the CDS-treated soils and was significantly higher than the PDS-treated soils (0.37 cmol/kg) and the control soils (0.13 cmol/kg). An increase in exchangeable K content was recorded for all treatments, including the Control all through the study, with no significant differences between the PDS-treated soils and the CDS-treated soils. The highest exchangeable K value recorded from the study (0.65 cmol/kg), which differed significantly from other treated soils, was however recorded from PDS at 16 weeks of incubation, and the least exchangeable K value (0.13 cmol/kg), which also differed significantly from others, was recorded from control at 4 weeks of incubation.

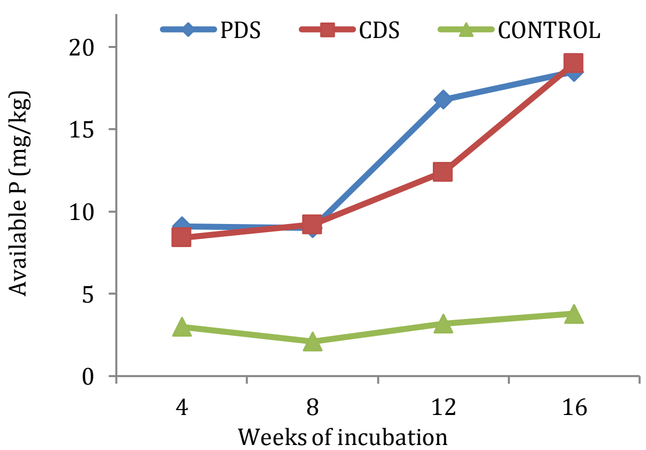

Figure 5. Acailable P contents (mg/kg) of the composts-treated soils obtained during incubation study

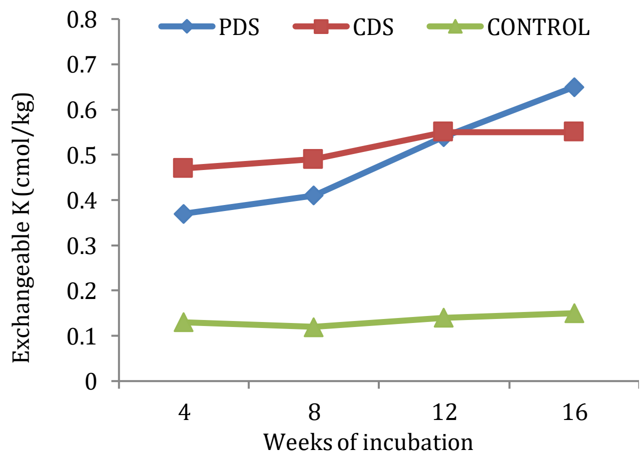

Figure 6. Exchangeable K contents (cmol/kg) of the composts-treated soils obtained during incubation study

Effects of PDS and CDS on exchangeable Ca contents of treated soils

Figure 7 shows that the exchangeable Ca content of the treated soils reduced with weeks of incubation. A noticeable reduction in exchangeable Ca content was observed from 8 weeks of incubation. The PDS gave significantly higher exchangeable Ca values than CDS-treated soils all through the period of incubation. The PDS recorded the highest exchangeable Ca value (8.4 cmol/kg) at the 16th week of incubation whereas the exchangeable Ca values obtained for CDS throughout the incubation period were the lowest (2.5, 10.5, 9.5 and 1.6 cmol/kg at 4, 8, 12 and 16 weeks respectively), conspicuously lower than the exchangeable Ca values obtained in the control soil.

Effects of PDS and CDS on exchangeable Mg contents of treated soils

The same trend as in exchangeable Ca was observed in the values of exchangeable Mg obtained in the incubation studies (Figure 8). The exchangeable Mg contents of soils treated with PDS and CDS composts reduced with weeks of incubation. Unlike in Ca where an increase in the recorded values experienced an increase till 8 weeks of incubation, a continuous decrease was recorded for exchangeable Mg values. The PDS-treated soils were significantly the highest in exchangeable Mg values recorded at all weeks. The highest exchangeable Mg value of 7.9 cmol/kg was recorded from PDS at week 4 while the CDS was the lowest in exchangeable Mg values (1.7 cmol/kg), lower than the control sample, at week 16 of the study.

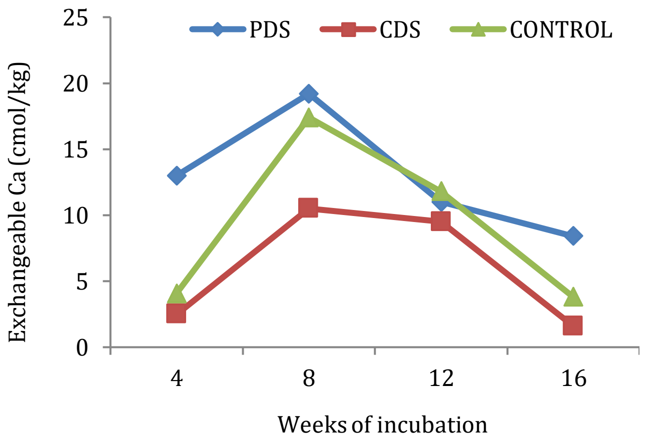

Figure 7. Exchangeable Ca contents (cmol/kg) of the composts-treated soils obtained during incubation study

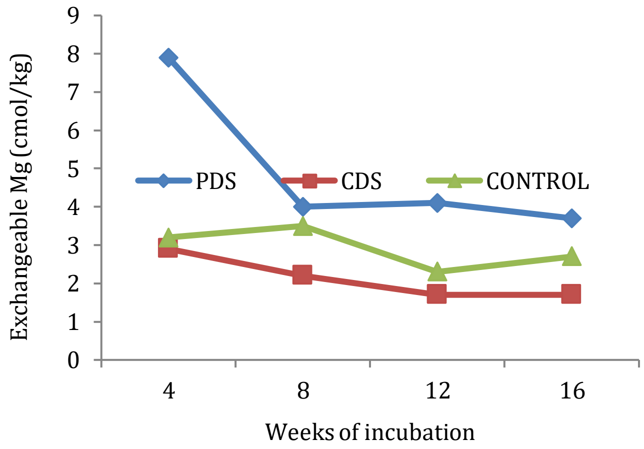

Figure 8. Exchangeable Mg contents (cmol/kg) of the composts-treated soils obtained during incubation study

Discussion

In this study, the two composts—PDS and CDS—attained the thermophilic stage by the third turning (6 weeks into composting), reaching temperatures of 62 °C and 66 °C for PDS and CDS, respectively. This increase in temperature signifies intense microbial activity within both compost heaps (Nemet et al., 2021). The thermophilic stage is crucial for compost quality enhancement, as it ensures the destruction of pathogens and weed seeds (Muller-Samann and Kotschi, 1994; Ryckeboer, 2001). From weeks 18 to 22, the constant and lower temperatures (24–25 °C) without any reheating upon turning indicated that the piles had entered the curing stage. Curing is associated with reduced microbial activity and the stabilization of the end products of composting (Fuchs, 2010; Nemet et al., 2021). Moreover, curing allows the growth of certain fungi and enhances the disease-suppressive potential of composts (Muller-Samann and Kotschi, 1994). However, proper management of the curing stage is essential to prevent recontamination with weed seeds (Nemet et al., 2021).

The slightly higher temperature and more rapid reactions observed in the CDS heap may be attributed to more vigorous microbial activity driven by the higher C:N ratio in cattle dung, which reflects greater lignin content. Orlando and Borja (2020) reported lignin contents of 11.48% in cow dung and 4.17% in poultry dung. This implies that nutrients in poultry dung are released more rapidly than those in cow dung. The dark brown to black color of the composts at 22 weeks is a recognized indicator of compost maturity (EPA, 1994). At this stage, a reduced C:N ratio was also observed, suggesting increased decomposition and mineralization resulting from microbial activity (Nemet et al., 2021).

The observed increase in pH was related to elevated levels of exchangeable bases. Muller-Samann and Kotschi (1994) reported that increased cation exchange capacity and alkalinity often occur by week 22 of composting. This is likely due to microbial breakdown of organic matter, leading to the release of exchangeable cations. The improved nutrient status of the composts may be attributed to the decomposition of waste materials by a wide range of microorganisms, including bacteria and fungi, generating essential soil nutrients. The consistently higher nutrient values recorded in CDS composts at both 2 and 22 weeks may be linked to the more intensive microbial activity driven by the higher C:N ratio in cattle dung.

In the early stages of compost application, a slight increase in soil acidity was observed. This suggests that soil reactions may become more acidic during the initial weeks of incubation. Regardless of treatment, soil pH decreased with incubation time, in agreement with the findings of Roy and Abdul Kashem (2014). Similarly, Gogoi et al. (2021) reported decreasing pH values in compost-treated soils. However, after 12 weeks of incubation, pH increased again, supporting a more favorable environment for plant growth. This pH increase may be associated with the rising levels of exchangeable potassium in the treated soils.

The initial decline in soil organic matter (SOM) across all treatments, including the control, aligns with the findings of Roy and Abdul Kashem (2014), who reported an initial increase followed by a gradual decrease in SOM content with extended incubation.

Nitrogen immobilization observed at week 8 in both compost treatments may have resulted from nitrogen fixation by the expanding microbial population actively decomposing the organic materials (Lim et al., 2018; Nahm, 2023). This pattern of N release may also be influenced by the quality and composition of the compost materials (Rayne and Aula, 2020). Abbasi et al. (2015) stated that the rate of nitrogen release or immobilization from organic sources is dependent on their nitrogen content. They noted that materials with less than 24 g N/kg tend to immobilize nitrogen. Since the N content of the composts in this study was below this threshold, immobilization likely dominated during early incubation stages, particularly around week 8. Eghball et al. (2002) and Shin et al. (2006) emphasized that nutrient mineralization varies depending on the type and composition of organic amendments. Ribeiro et al. (2010) also found that nitrogen release depends on the carbon structure of compost materials. This supports the finding that nitrogen in PDS compost may be mineralized more quickly than in CDS compost. Chadwick et al. (2000) and Fangueiro et al. (2010) further established that the C:N ratio is a key determinant of nitrogen mineralization. Fawole et al. (2019) observed a decrease in compost nitrogen content at week 8, followed by increases at weeks 12 and 16, a pattern consistent with our findings. These trends suggest that PDS and CDS composts are better suited for long-term crops, as some fast-growing vegetables like Amaranthus may mature before nutrient release peaks. Therefore, the application of these composts is more profitable for long-term vegetable and crop production.

The increase in available phosphorus (P) across all treatments during incubation indicates substantial mineralization of organic P in the composts. This supports the suitability of both composts for improving P availability in soils. Fawole et al. (2021) reported similar findings, highlighting the suitability of composts for both short- and long-term vegetable production. Distinct peaks in phosphorus availability observed between the two composts suggest that nutrient release varies depending on compost composition and maturity (Bakayoko et al., 2009).

Exchangeable potassium (K) also increased throughout the incubation period, though with different peak times for each compost. This indicates that the nutrient release dynamics are influenced by the specific composition of the composts. According to Rayne and Aula (2020), nutrient release from livestock manures depends on their physical and chemical characteristics. In this study, up to a 400% increase in soil K was observed in treated soils compared to the control. While there is no clearly defined upper limit for soil K levels, excessive K can lead to luxury consumption by plants and may interfere with the uptake of other nutrients. High soil K levels may result in K/Ca and K/Mg antagonism, reducing calcium and magnesium uptake (Xie et al., 2021). Moreover, elevated K can negatively affect boron, iron, and molybdenum availability, though it may enhance copper, manganese, and zinc uptake (Nguyen et al., 2017).

The compost treatments improved the NPK content of soils compared to the untreated control. This is consistent with the findings of Gogoi et al. (2021), who reported increased NPK levels in compost-amended soils. A decline in calcium and magnesium content was observed with increasing incubation time, in agreement with Tito et al. (2020), who also noted a decrease in calcium, although magnesium increased in their study.

Soils treated with PDS recorded higher values for pH, SOM, N, P, K, Ca, and Mg throughout the incubation study. This indicates that PDS compost facilitated greater nutrient mineralization and may support improved and sustainable crop yields. Azad et al. (2022) similarly reported that poultry manure improved SOM, cation exchange capacity, base saturation, and yield output more effectively than cow dung compost.

Conclusion

This study was conducted in three phases to achieve the following objectives: (i) to determine the nutrient compositions of poultry droppings, cow dung, and sawdust; (ii) to characterize the two composts produced from these materials; and (iii) to investigate the dynamics of soil reaction (pH), organic matter, and macronutrients (nitrogen, phosphorus, potassium, calcium, and magnesium) following the addition of these composts through incubation studies.

The results of the study revealed that composting effectively reduced the particle size of raw materials, converting them into a soil-like substance with a lower carbon-to-nitrogen (C:N) ratio, increased pH, enhanced cation exchange capacity (CEC), and reduced heavy metal content. The compost produced from poultry dung and sawdust (PDS) demonstrated faster nutrient mineralization compared to cow dung and sawdust (CDS), due to the lower C:N ratio in poultry dung.

A temporary decline in nitrogen content was observed between weeks 4 and 8 of incubation, followed by a stabilization from week 12 onward. The application of both composts significantly improved the availability of major macronutrients, particularly nitrogen, phosphorus, and potassium, in the treated soils. These values were notably higher than those in the untreated control soils. However, a gradual decline in calcium and magnesium contents was observed over the incubation period.

Among the treatments, PDS consistently resulted in higher values of soil pH, organic matter, nitrogen, phosphorus, potassium, calcium, and magnesium. Therefore, composted poultry dung with sawdust is recommended as an effective organic amendment for improving soil fertility, particularly in terms of pH regulation, organic matter enrichment, and macronutrient supply. Cow dung composted with sawdust may serve as a suitable alternative when poultry dung is not readily available.

Finally, it is recommended that the study be extended for a longer incubation period to further explore the long-term effects of these organic nutrient sources on soil chemical properties and nutrient dynamics.

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A Combined application of compost and mineral fertilization enhances plant growth and soil fertility in calcareous clay loam soils

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Abstract

Pot experiment was implemented to investigate the effect of compost soil application with and without mineral fertilizers on the plant growth and fertility of calcareous clay loam soils. Randomized complete block design with four replication was used to evaluate the following treatments: i) Control with no compost or fertilizer addition (C); ii) Compost at a rate of 20 ton ha^{1} (Co); iii) Mineral NPK fertilizer as di-ammonium phosphate and potassium sulfate at a rates of 700 kg and 500 kg ha^{-1}, respectively; (F) and iv) Combined compost and mineral fertilization (CoF). Pots filled with 4 kg soil and seeded with maize were periodically watered to reach field capacity water content. At flowering stage samples of soil and plants were taken were for analysis. The results indicated that application of compost with and/or without mineral fertilizer significantly increased plant growth and nutrients uptake. Moreover, soil organic matter, cation exchange capacity and nutrient contents were also significantly increased by the same treatments. However, the positive effect of the combined compost and mineral fertilization was better than the effect of separate application of each. The obtained results highly recommend the combined application of compost and mineral fertilizers.

Keywords: Compost, Mineral fertilizer, Maize, Calcareous soil.

Introduction

Soil degradation caused by natural and/or anthropogenic activities is a major worldwide problem that spread at an alarming rate, threatening global food production system. It was estimated that 52 percent of agricultural land world-wide is moderately or severely degraded, (FAO, 2021). One of the consequences of soil degradation is the shrinkage in agricultural soils and the loss of soil organic matter (OM), fertility, and productivity (Maximillian et al., 2019), which is considered vital for sustaining global food security (UN, 2022).

Therefore, increasing food production can mainly be achieved through increasing productivity of the existing land, which can be achieved through intensification with intensive use of agricultural inputs such as mineral fertilizers. Intensification, however, may lead to degradation and deterioration of soil OM, soil fertility and other negative impact on the soil quality (Gupta, 2019; Chang et al., 2021). Although, soil fertility and soil OM are vital components of soil health, but unfortunately have been depleted by intensive farming and/or mismanagement practices. (AbdelRahman et al., 2022). The decline in soil OM decreases soil fertility, water holding capacity, biodiversity and aggregation and structure formation. (Eden et al., 2017).

Intensive use of mineral fertilizers may lead to negative impact on the environment and may lead to soil nutrient imbalances and decline in soil OM (Penuelas et al., 2020; Penuelas et al., 2023). When applied with organic fertilizer however, mineral fertilizer besides supplying plant nutrients tend to enhance the availability of nutrients contained in organic sources. On the other hand, fertilization with organic fertilizers will enhance soil OM, improve soil fertility and create more favorable soil conditions (Eden et al., 2017).

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Eco-intensification instead is a recommended approach for integrated nutrient management to sustain food production while mitigating adverse environmental effect (Oyetunji et al., 2022). With regards to nutrients management, this can be achieved through adoption the 4R Nutrient stewardship concept, which imply the application of the right sources, rate, time, and place of nutrient application (Rusan, 2018). The right source of nutrient should consider the complementary use of both mineral and organic sources that suit and match the local soil, plant, and climate characteristics (Rusan, 2017, 2023). It has been reported that application of organic fertilizers in synchronization with inorganic fertilizer enhances soil structure, soil OM and soil microbial activities which consequently improve nutrient use efficiency. In addition, combined application of compost and inorganic fertilizers improves nutrient retention and supply and improves soil fertility and crop productivity.

Compost of animal and crop residue organic wastes is rich in OM and contained plant nutrients, therefore, can be used as an organic fertilizer, separately and/or in combination with mineral fertilizers (Adewopo et al. 2014). This is of more importance under arid and semiarid conditions, where soil OM play a vital role in enhancing soil water holding capacity and enhances mitigation and adaptation to climate change condition (Amundson et al. 2015). Besides, compost is less expensive than traditional organic fertilizers and mineral fertilizers. therefore, compost use might partially substitute the recommended rate of mineral fertilizer, thereby reducing production cost and potentially increasing farmers' income (Zaki et al., 2018).

Composts made from plant and livestock organic wastes have been commonly investigated and used as a more economically beneficial organic fertilizer for improving soil fertility and crop production (Hernández Rodríguez et al., 2017; Zaki et al., 2018; Banuwa et al., 2020). Limited research has been conducted on the use of plant and food-based compost made from municipal organic waste. Therefore, the objective of this study was to determine the positive effect of combined application of plant and food-based compost and mineral fertilizers in comparison with their individual applications on plant growth and soil parameters under calcareous clay loam soils.

Material and Methods

A greenhouse pot experiment was conducted to determine the effect of compost fertilization with and without mineral fertilizer on plant growth and soil properties under calcareous clay loam soil. The soil was collected from the Research Center at Jordan University of Science and Technology (JUST). The air-dried and sieved through a 5 mm sieve soil was analyzed for texture by hydrometer method (Gee et al., 1986); bulk density by the core method (Blake and Hartge, 1986); soil pH and soil EC were measured on 1:1 soil : water suspension (Mclean, 1982 and Rhoades, 1982a, respectively); OM using Walkley–Black method (Nelson and Sommers, 1982); cation exchange capacity (CEC) by Rhoades (1982b); total N by Kjeldahl (Nelson and Sommers, 1980); available P by extraction with sodium bicarbonate (Olsen et al. 1954); exchangeable K by extraction with 1 M NH_4OAc (Thomas 1982); $CaCO_3$ by acid neutralization (Richards, 1954); heavy metals (Fe, Mn, Zn) by DTPA-extractable microelements (Lindsay and Norvell, 1978). Soil properties are shown in Table 1.

Table 1. Soil characteristics before conducting the experiment.

	Value
Soil pH	8.18
Soil EC, dS m^{-1}	0.61
CEC, Cmol kg^{-1}	34.32
OM, %	1.18
$CaCO_3$, %	13.38
Soil N, %	0.01
Soil P, mg kg^{-1}	7.10
Soil K, mg kg^{-1}	452
Bulk density, g cm^{-3}	1.38
Soil Texture	Clay Loam

Randomized complete design was used to investigated the following treatments in four replications:

1. Control (C)
2. Application of Compost (Co)
3. Application of NPK (F)
4. Application of Compost and NPK (CoF)

Every pot (22.5 cm top diameter x 16.5 cm bottom diameter x 18 cm hight) was filled with 4 kg air-dried soil. According to the treatment, N and P were added to each pot as di-ammonium phosphate, $(NH_4)_2HPO_4$ (DAP) while potassium as potassium sulfate, K_2SO_4 (PS). The recommended rate of DAP and PS were applied based on local experience at a rate of 700 kg and 500 kg per hectare, respectively. Compost of municipal organic waste was applied at a rate of 20 tons ha^{-1}. Four seeds of maize were seeded in each pot. After germination plants were thinned to three similar plants per pot. Pots were watered periodically to reach the field capacity water content. Time of irrigating plants was determined by weighing each pot every two days and adding water to achieve the initial wet weight of the 100% field capacity.

Table 2. Compost characteristics.

Properties	Values
pH	7.90
EC, dS m^{-1}	2.51
OM, %	60.13
Bulk density, g cm^{-3}	0.46
N, %	2.22
Soil P, mg kg^{-1}	0.58
Soil K, mg kg^{-1}	1.42

After the beginning of flowering stage observed after 8 weeks of growth, the above ground plants were harvested, fresh weight was measured, then were oven-dried at 70°C and the oven dry weight was determined. Thereafter, the oven dried plants with a laboratory mill with 0.5 mm sieve were milled to a fine powder. The milled plant samples were analyzed for total N using a modified micro-Kjeldahl digestion procedure (Bremner and Mulvaney, 1982), dry ash digestion total P using Vanadate–Molybdate–Yellow method and total K with the flame photometry (Chapman and Pratt, 1961). The soil from each pot was thoroughly mixed and a representative sample was obtained and sieved through 2 mm sieve and analyzed for pH, EC, N, P, K as mentioned above.

General linear model (GLM) analysis was used to statistically analyze all data collected from this search with SAS version 9.0 (2002) software. Means subjected to analysis of variance (ANOVA) were according to Least Significant Difference LSD method at five percent level of significance P≥0.05.

Results

Plant Growth and Nutrient Uptake

Treatments effect on plant growth is presented in Figure 1. The control treatment, where no mineral fertilizers or compost were added resulted in the lowest plant height and dry weight. Addition of compost (Co) resulted in higher plant height and dry weight compared to the control but remained lower than that obtained with mineral fertilizers application (F) and combined application of mineral fertilizers and compost (CoF). This suggest that the positive effect of compost application alone, was not equivalent to the effect of application of recommended mineral fertilizers, suggesting the compost does not provide all nutrients required by the plant. However, when both mineral fertilizers and compost were simultaneously applied, they resulted in the highest plant growth. Similar trends were obtained with treatments effect on the content and uptake of macronutrients which are presented in Figure 2 and Figure 3. Plant content and uptake of nitrogen (N), phosphorous (P) and potassium (K), obtained with mineral fertilizers application were higher compared to the compost treatment but remained lower that that obtained with combined application (CoF).

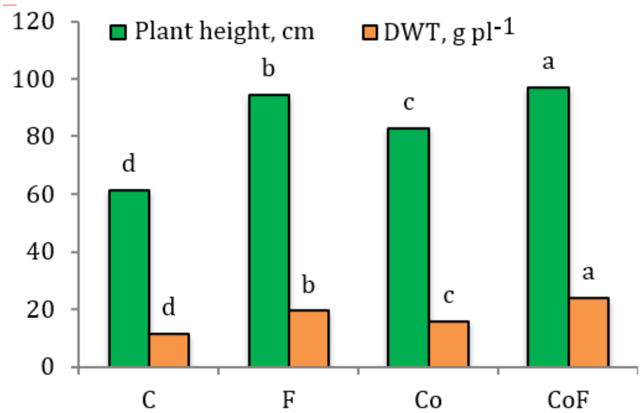

Figure 1. Plant growth parameters as affected by compost and mineral fertilization. Columns with similar letters are not significantly different at P≤0.05

The positive impact of combined application of mineral fertilizers and compost on plant growth and plant nutrient suggest the complementary and supplementary positive effect of compost when applied simultaneously with mineral fertilizers. Such effect could be attributed to the positive effect of compost on the soil biological, chemical, and physical properties due to high porosity and low bulk density of the compost, as well as the positive effect of the high OM of the compost.

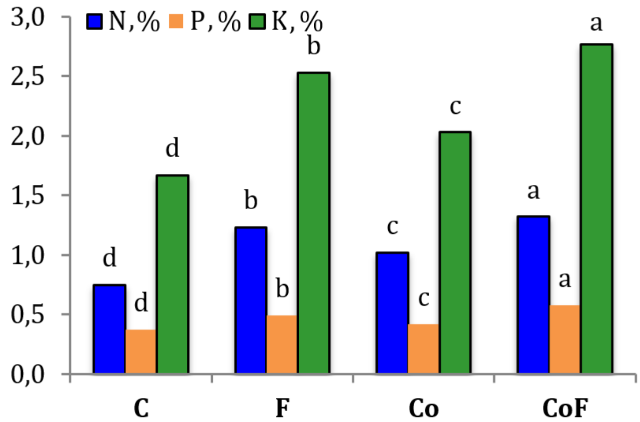

Figure 2. Plant macronutrient content as affected by compost and mineral fertilization. Columns with similar letters are not significantly different at P≤0.05

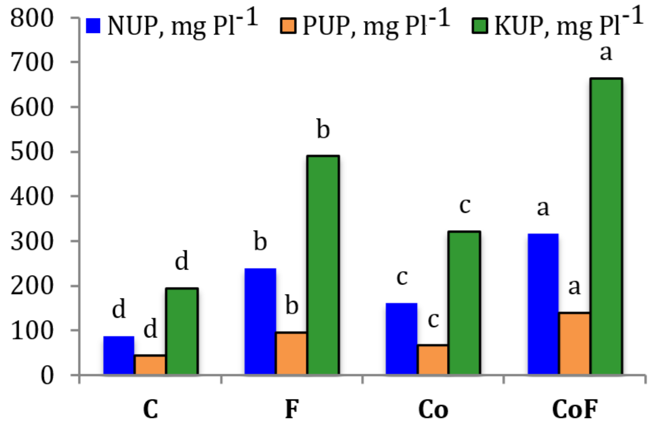

Figure 3. Plant macronutrient uptake (UP) as affected by compost and mineral fertilization. Columns with similar letters are not significantly different at P≤0.05

Plant content and uptake of micronutrients as influenced by the investigated treatments are shown in Figure 4 and Figure 5. Unlike the trend with macronutrients, the application of compost alone resulted in higher content and uptake of iron (Fe), manganese (Mn) and zinc (Zn) compared to the mineral fertilizers application. This can be expected due to partially due to the micronutrients content of the added compost and partially due to the indirect effect of the organic compounds contained in the added compost which enhances solubility and availability of the soil micronutrient through chelation reactions. Combined application of mineral fertilizers and compost resulted on additional positive effect on plant micronutrients content and uptake, which may suggest the complementary and supplementary positive effect of combined application of mineral fertilizers and compost.

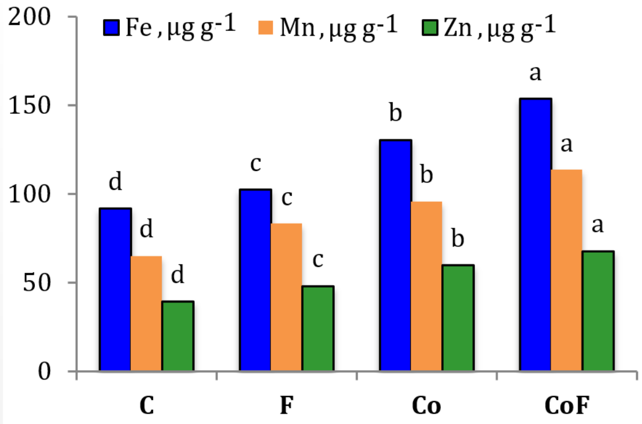

Figure 4. Plant micronutrient content as affected by compost and mineral fertilization. Columns with similar letters are not significantly different at P≤0.05

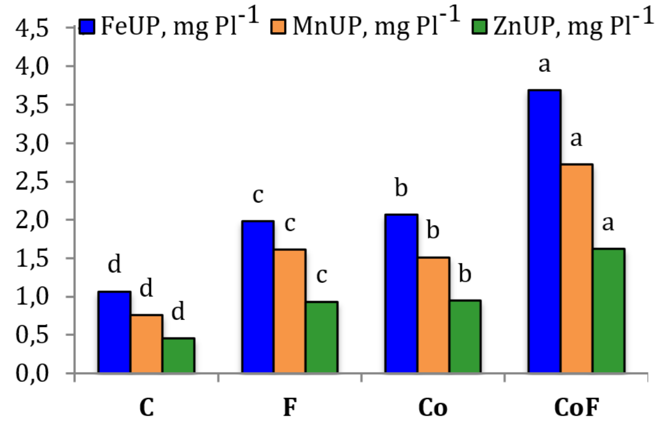

Figure 5. Plant micronutrient uptake (UP) as affected by compost and mineral fertilization. Columns with similar letters are not significantly different at P≤0.05

Soil Properties

The treatment effect of soil pH and soil EC (Electrical conductivity) are shown in Figure 6 and Figure 7, respectively. Soil pH was lowered similarly by the application of mineral fertilizer and compost whether they were applied separately or simultaneously compared and remained higher than that obtained with the control. However, the increase in soil EC by compost application with and without mineral fertilizer, is attributed to the relatively high EC of the compost (2.5 dS m^{-1}).

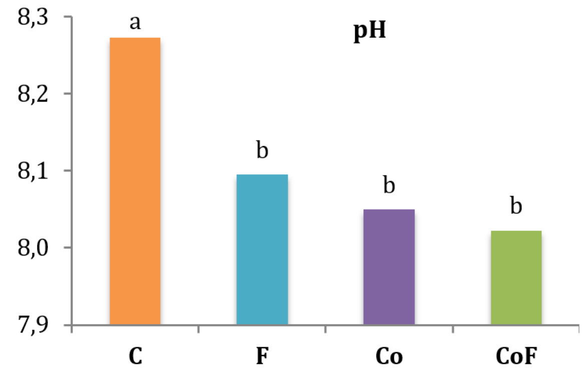

Figure 6. Soil pH as affected by compost and mineral fertilization application. Columns with similar letters are not significantly different at P≤0.05

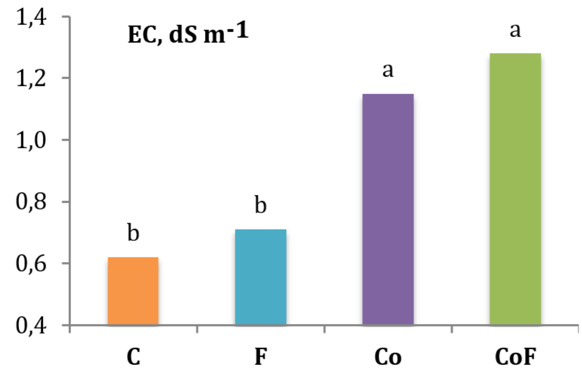

Figure 7. Soil EC as affected by compost and mineral fertilization application. Columns with similar letters are not significantly different at P≤0.05

Soil OM (Figure 8) and soil cation exchange capacity (CEC) (Figure 9) were increased with separate application of compost and with combined application of mineral fertilizer and compost. The high percentage of OM of compost (60.3%) resulted in increasing the soil OM with comport application. OM has a strong effect on several properties of soil including increasing the CEC, which was observed in this study following compost application. On the other hand, compost application decreased soil bulk density (Bd%) (Figure 10), which is attributed to the higher porosity and lower bulk density of the applied compost.

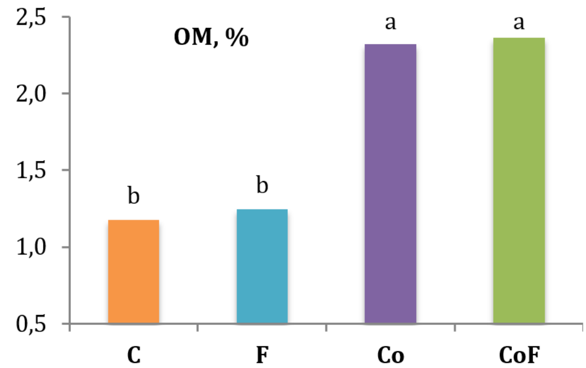

Figure 8. Soil organic matter (OM) as affected by compost and mineral fertilization. Columns with similar letters are not significantly different at P≤0.05

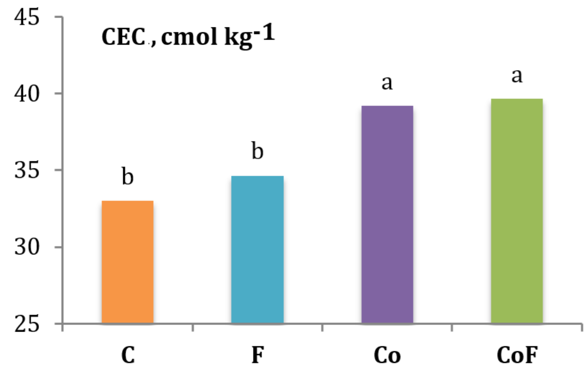

Figure 9. Soil CEC as affected by compost and mineral fertilization. Columns with similar letters are not significantly different at P≤0.05

Soil N, P and K contents as influenced by the treatments are shown in Figure 11, Figure 12, and Figure 13, respectively. Soil N was the lowest for control and significantly increased with compost application. The application of mineral fertilizer with and without compost resulted similarly in higher soil N compared to the control and compost treatments. Similar trends were observed with treatments effect on soil K. On the other hand, soil P was affected differently. The control resulted in the lowest soil P level. However, soil P increased by the application of mineral fertilizer, then by compost, then by combined compost and mineral fertilization.

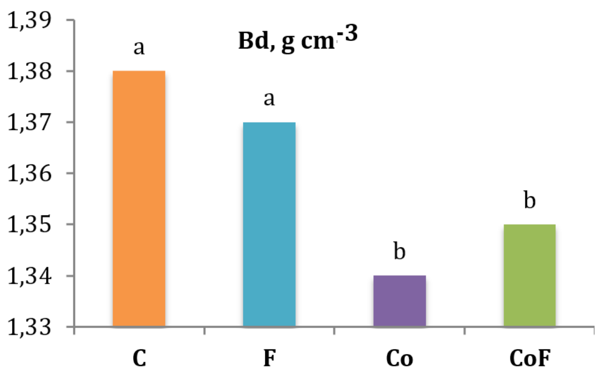

Figure 10. Soil Bulk density as affected by compost and mineral fertilization. Columns with similar letters are not significantly different at P≤0.05

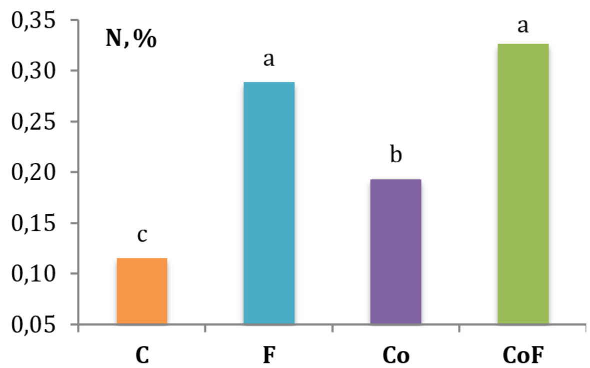

Figure 11. Soil N as affected by compost and mineral fertilization. Columns with similar letters are not significantly different at P≤0.05

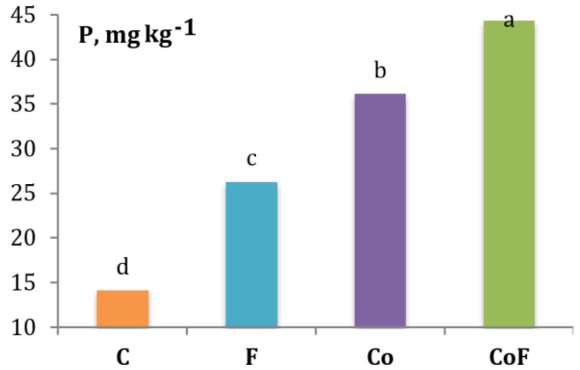

Figure 12. Soil P as affected by compost and mineral fertilization. Columns with similar letters are not significantly different at P≤0.05

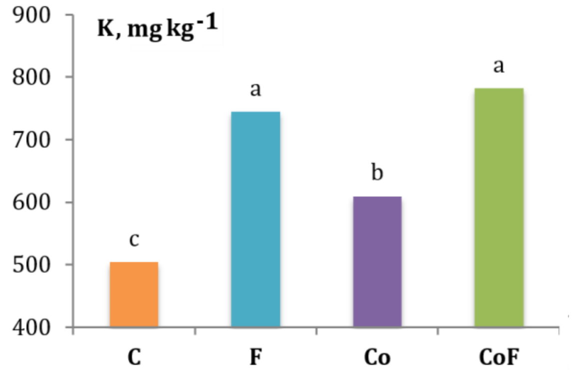

Figure 13. Soil K as affected by compost and mineral fertilization. Columns with similar letters are not significantly different at P≤0.05

Discussion

The complementary use of mineral and compost resulted in the highest plant growth and nutrient uptake, suggesting the advantage of their combined and complementary use. Although, the separate application of mineral fertilizer or the separate addition of compost increased plant growth parameters and soil fertility compared to the control, however, neither of them achieved these parameters as their combined use did. Compost fertilization proved to increase crop yields, increase soil OM, improve water holding capacity, lower soil bulk density and decrease soil erosion rate (Al-Rumaihi et al., 2020; Petrescu-Mag et al., 2020).

Nutrient uptake increased with both compost and mineral fertilization whether they were applied individually or in combination. Other researhcers (Malézieux and Bartholomew, 2003) found that plant uptake of N, P, K Fe and Zn by pinapple increases with compost application . Nardi et al. (2002) reported that the released humic substances during mineralization of compost stimulate root growth and proliferation and improves plant growth and nutrient uptake.

Nevertheless, applying compost alone did not increase nutrient uptake to the extent achieved with mineral fertilizer, indicating that compost alone cannot supply all plant nutrient requirements, unless applied with mineral fertilizers. Thus, compost will partially provide the crops with their nutrient requirement and will partially substitute and compensate for the use of mineral fertilizers. Nardi et al., (2002) reported that compost application compensated for 40% of the fertilizer requirement of crop.

As for plant micronutrient (Fe, Mn and Zn) uptake, it was observed that the highest uptake was with combined application. Their uptake with separate application of compost was higher than the control and even than the separate application of mineral fertilizers. The organic compounds provided by compost application could be attributed to the enhancement of the availability of the indigenous soil micronutrients through chelating them into available forms to plant uptake (Rusan et al., 2017).

Several researchers reported the beneficial use of composts of various sources of organic waste as a soil amendment and a source of nutrients and OM to enhance yield and soil fertility (Cahyono et al., 2020). Other researchers attributed the benefit of compost application to the direct effect by supplying nutrient and/or to the indirect effect thought enhancing soil microbial activities and other soil fertility parameters such as water holding capacity, soil structure and others (Zaki et al., 2018; Banuwa et al., 2020). Compost is considered a slow-release fertilizer, and therefore, minimizes losses and enhances nutrient use efficiency. So is highly recommended to apply it in combination with soluble mineral fertilizers as was reported by several scientest (Adugna, 2016; Ning et al., 2017). As for the increase in soil EC associated with compost application, which was obtained in our study, it can be explained by the relatively high compost EC and by the release of minerals during mineralization (Liu et al., 2011). Soil EC increased with compost application was reported by other researchers (Sarwar et al., 2010). Other researchers explained the increase in soil EC with compost application to the release of mineral ions during compost decomposition and mineralization (Hemidat et al., 2018, 2022).

Soil fertility attributes have positively been affected by compost application. Our study demonstrated the positive effect of compost application with and without mineral fertilizers on soil pH, OM, CEC, and bulk density. One of the main benefits of compost soil application is the increase in soil OM, which has several positive effects on various soil biological, chemical, and physical properties of the soil (Bhatacharyya et al., 2008; Efthimiadou et al., 2010). Other investigators have reported an increase in soil OM and NUE with combined organic and inorganic fertilization (Liu et. al., 2008), and attributed that to the high organic content of the compost as well as to the positive effect of organic matter on enhancing the bioavailability of other mineral nutrients..

The high OM content and low bulk density of the applied compost explained the positive effect on these attributes of the soil. Decreased soil bulk density and increased soil OM obtained in our study, due to lower bulk density and higher OM of the applied compost with and without mineral fertilizers, favorably influences soil physical conditions and plant growth (Leroy, et al., 2008). Soil CEC increase with compost application was attributed to the high CEC of the humic compounds and carboxyl and phenolic functional groups of the compost (Wichuk and McCartney, 2010). Other researchers reported a decrease in soil bulk density and improved soil aggregation with compost application (Cahyono et al., 2018), owing to the positive effect of organic matter on soil physical properties.

Soil nitrogen (N) and potassium (K) contents were lower with compost application compared to the control but were higher than those obtained with the combined aaddition of compost and mineral fertilizers. As for soil P unlikely, it was increased more by separate application of compost than by mineral fertilization. It is not clear why soil P was affected differently compared to soil N and soil K, but one of the possible explanations could be the indirect positive of organic compounds provided by compost on the enhancement of availability of the unavailable forms of soil P. It has been reported that organic compounds in the soil tend to coat soil P and prevent it from being precipitated into unavailable forms. These findings agree with the findings of other researchers, who reported an increase in soil N, P and K with combined organic and inorganic fertilization compared with control and mineral fertilization (Herencia et al., 2009). In addition, other researcher reported an increase in soil P, K and micronutrients with compost application (Sarwar et al., 2010).

The increase in soil nutrients with compost application could be attributed to the release of nutrient from compost to the soil during mineralization of compost (Adugna et al., 2016) and/or indirectly due to positive effect of compost on soil fertility. The increase in soil OM obtained with compost application farther enhances use efficiency of the jointly applied mineral fertilizers and increased nutrients content in the soil (Bhattacharyya et al., 2008; Bouajila and Sanaa, 2011).

Conclusion

The obtained results in this study recommend that the complementary use of compost and inorganic fertilizers has synergistic and positive effects on plant growth, nutrient uptake, and soil fertility parameters. Plant dry biomass, as well as macronutrient and micronutrient uptake were significantly increased with combined application of compost and mineral fertilizers. The lowest plant height and dry weight were obtained in the control followed by the mineral fertilizer's treatment. Compost application with and/or without mineral fertilizers favorably decreased soil bulk density. Additionally, compost application can partially substitute for the use of expensive inorganic fertilizers, thereby enhancing farmers' income and promoting the sustainability of food production system. Since the use of the compost made from municipality waste does not have high acceptance by farmers and local communities, it is recommended for future research to include the study of social factors affecting the adoption of the use of such compost.

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Soil enzymatic responses to long-term fallowing in Southern Taiga Forests

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Abstract

The largest area of land in Russia is located in the fallow state, there is a change in plant communities, physico-chemical parameters of soils and changes in the enzymatic activity of soils. To analyze the condition of fallow and undisturbed soils, we studied different-aged changes in the main physico-chemical parameters of soils, analyzed the features of morphological structure of soils, and also studied the enzymatic activity of soils of such classes of enzymes as hydrolase and oxidoreductase. Sampling was carried out from the upper humus-accumulative horizons of 13 soil sections of the Leningrad and Novgorod regions of Russia. As a result of research, it was revealed that transition of lands to fallow state leads to transformation of soils towards zonal series of soils. Soil transformation is accompanied by a decrease in pH value, content of biogenic elements, with an increase in the content of carbon and biogenic elements in old-age plots. The study of enzyme activity in soils showed that the activity of the studied enzymes at different sites varies differently, depending on land use. Significantly higher activity of oxidoreductases class was noted for soils in which transformation of wood residues takes place and O horizon is formed. A comparative assessment of the biological activity of the studied soils was given using the indicator of total relative enzymatic activity (indicator representing the total biochemical activity of soil based on enzyme analysis). According to the comparative assessment of soil biological activity, it was found that the biological activity increases with increasing time of soils being in fallow state. Thus, to restore soil biochemical activity and agroecosystem stability, long (30-year) fallow periods with secondary forest formation should be maintained, which provides neutral pH, organic carbon accumulation, and maximum enzymatic activity superior to both recently abandoned and arable lands.

Keywords: Hydrolase, North-West of Russia, Oxidoreductase, Podzols, Retisols.

Introduction

Worldwide, the area of abandoned land is 220 million hectares, of which Russia accounts for almost 20% (Lurie et al., 2010). This high percentage of abandoned land was caused by the economic depression that occurred in Russia in the early 1990s, due to political factors. Therefore, since the early 1990s, there has been a stable trend in the country's agriculture to remove previously sown arable land from active agricultural rotation (Nechaeva, 2023). Some of these lands were built up by cities and industrial facilities. But the largest part, about 91% of arable land in Russia, after being abandoned underwent a process of restoration (Lurie et al., 2010). Being a favorable environment for the restoration of natural landscapes, post-agricultural lands began to develop in the direction of formation of natural ecosystems, given the natural climatic zone and overgrow meadow, shrub and woody vegetation (Sorokina, 2016; Dmitriev and Lednev, 2016; Telesnina, 2017).

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Abandonment of agricultural land is an increasingly important problem in European countries (van der Sluis et al., 2014; Gabarrón-Galeote et al., 2015; Vacquie et al., 2015; Ustaoglu and Collier, 2018). Very acute, this issue is also in China, where large-scale agricultural land abandonment is taking place. According to the authors (Liu and Li, 2017), this is due to the fact that, as a result of China's ongoing rapid urbanization, an increasing number of rural workers are moving to urban areas, significantly reducing the rural agricultural workforce and contributing to farmland abandonment. Thus, the relevance of a comprehensive study of post-agricultural land processes is determined by the large scale of their distribution and high potential of their cultivation (Shchukin et al., 2018; Kalinina et al., 2018).

Since in parallel with the restoration of zonal vegetation, in the course of post-agrogenic evolution there is a change in their biological properties (Ovsepyan et al., 2017; Kurganova et al., 2021), the need to study the enzymatic activity of fallow soils is beyond doubt. According to various authors (Valkov et al., 1999; Zvyagintsev, 2005), enzymatic activity reflects the intensity of biological, physiological, biochemical processes occurring in the soil and is considered as a derivative of the combination of abiotic, biotic and anthropogenic factors of soil formation (Sun et al. 2022; Peng et al., 2024). Therefore, the biological activity of soil is crucial importance in the process of soil formation, development and degradation. The most frequently used indicator of potential biological activity is the soil enzymatic activity (Galstyan, 1974; Gorbtsova et al., 2017; Gedgafova et al., 2023).

Some of the most commonly considered enzymes are the classes of hydrolases (invertase, phosphatase, urease) and oxidoreductases (dehydrogenase, catalase). Dehydrogenases (DHA) is an indicator of oxidative metabolism in soil and microbial activity. The functioning of dehydrogenases is related to many biochemical processes in soil, including greenhouse gas emissions. Catalase (CAT) is an enzyme that catalyzes the decomposition of hydrogen peroxide into water and oxygen (Lemanowicz et al., 2020). Some of the most commonly studied hydrolytic enzymes are phosphatase (PHA), urease (Ure) and invertase (INV). PHA enzyme catalyze the hydrolysis of phosphoric acid esters and phosphoric acid anhydrides with the release of soluble phosphate from organic phosphorus and improvement of the phosphorus cycle. Thus, PHA activity can be used as an indicator of inorganic phosphorus availability to plants and microorganisms. Another hydrolytic enzyme Ure catalyze the hydrolysis of urea to CO_2 and NH_3 and helps to control soil quality as influenced by management practices and nitrogen content after urea application (Adetunji et al., 2017). Another hydrolytic enzyme INV is often used as an indicator of carbon cycling, which cleaves carbohydrate polymers, releases simpler sugars, thereby increasing soluble nutrient content of soil, mediates carbon transformations and produces major energy sources for soil microorganisms (Sardans et al., 2008). Soil enzymes affect essential soil processes such as plant decomposition, mineralization of soil organic matter, and release of nutrients into the soil through decomposition of organic residues and microbial activity (Dotaniya et al., 2019; Sobucki et al., 2021). Enzymes can be used to assess changes in the microbial community due to environmental changes or anthropogenic activities such as land use changes (Vikram et. al., 2024). It is known that due to the rapid response of the enzyme pool to many environmental changes, enzymatic activity is detected well before changes in other soil quality indicators (Zhang et al., 2015). The hypothesis of this work is that there will be a change in soil enzyme activity as a result of land use change and transition to fallow state. This study aimed to evaluate enzymatic activity across fallow soils of different ages in the Southern Taiga, and to apply a relative assessment approach.

Material and Methods

Study area

This study was carried out in the northwestern region of Russia, as follows Leningrad and Novgorod regions. The research area is located within the final moraine zone of the Valdai glaciation, characterized by widespread moraine deposits. The study areas are located on the plain and characterized by a low elevation difference of about 20 meters.

The region located within the southern taiga bioclimatic zone, where Podzols and Retisols dominate well-drained watersheds, while Histosols and Gleysols prevail in waterlogged areas. Climatic conditions feature an average annual precipitation of 587 mm, with evapotranspiration reaching around 430 mm. The mean annual temperature is 4.3 °C.

The Ban'kovo village area (Leningrad region) exhibits an extended agricultural history, with fallow soils ranging in age from 40 to 120 years. All investigated soils developed on uniform parent material - water-glacial sandy loams with puddled structure, underlain by red-brown moraine loams at a depth of 70-80 cm. The natural vegetation of the study area is a pine-birch-blackberry forest.

Soils of 20-year-old fallow, agricultural and undisturbed lands were studied in the area of Belogorka village (Leningrad region). The relief of this territory is characterized by relatively leveled surface. Soil-forming rocks are represented by local red-colored moraines with significant admixture of Devonian rocks. The study area belongs to the southern taiga subzone. Pine forests with admixture of spruce, birch and aspen prevail.

In the area of Borovichi city (Novgorod region), re-involved 30-year-old soils of fallow lands, agricultural soils and undisturbed soils were investigated. The study plots are located at a distance of no more than 700 m from each other and represent a single agro-landscape of the former agro-holding. The study areas are presented in Figure 1.

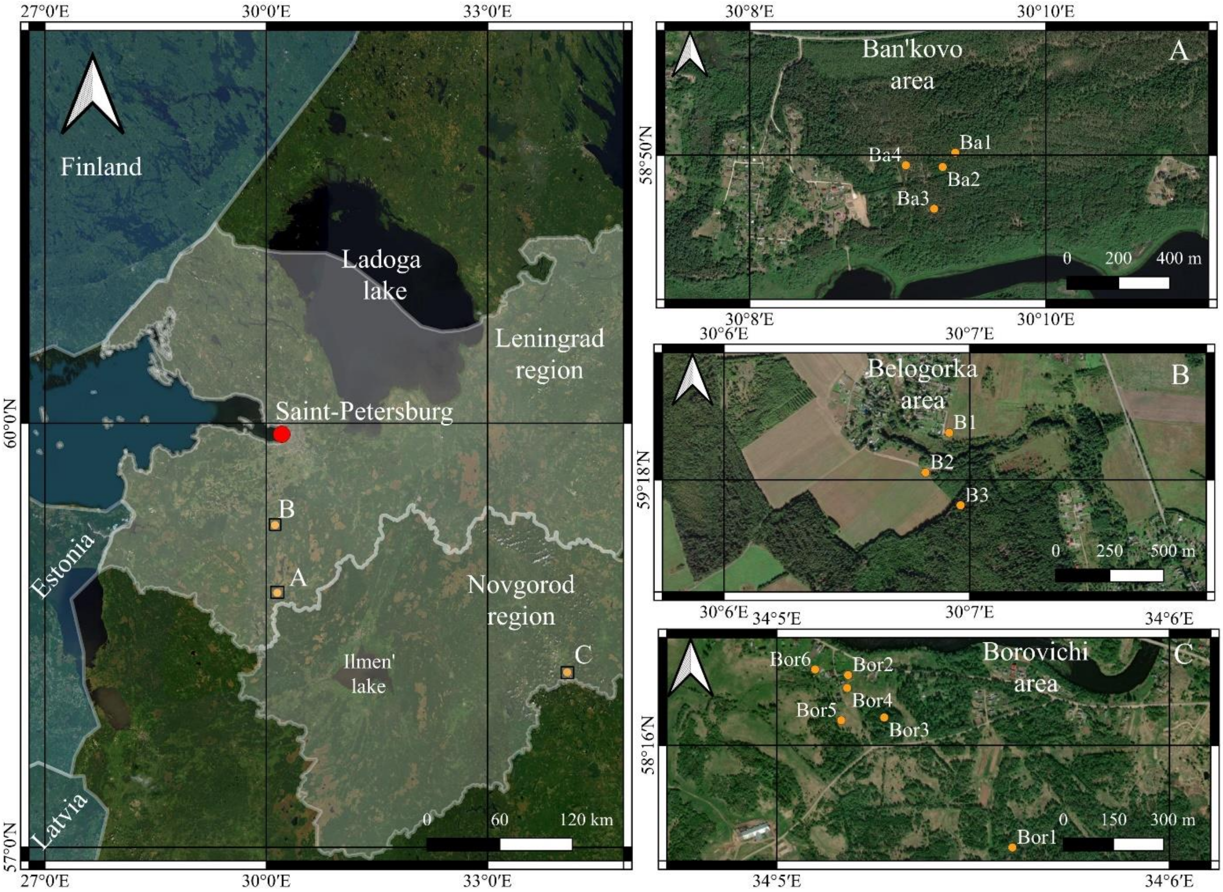

Figure 1. Location of the study area in the north-west of Russia

The selection of data is determined by the scope of soils of fallow lands formed on sandy parent materials (Ban'kovo), as well as silt-clay materials (Belogorka). Such diversity allows us to consider the features of transformation of the two leading soil types of the taiga-forest zone. The site in the Novgorod region (Borovichi) is characterized by soil formation as a result of transition to fallow state 30-years-ago, as well as by different type of agricultural use.

Differences in soil formation conditions and type of agricultural use determine the diversity of studied soils. The use of Podzols and Retisols in agriculture has a significant impact on the formation and biological indicators of soils, which are subject to ongoing changes and therefore require close attention and comprehensive study. Description of the studied soils are presented in Table 1.

Methods

Soil samples were collected from the key work sites to analyze physico-chemical and biological parameters of soils. Sampling was carried out from all studied soil horizons in order to trace the dynamics of enzymatic activity in soils of fallow lands and reclaimed fallow soils. The depth of sampling ranged from 0 to 70 cm and depended on the presence in the soils of the processes associated with the transition to fallow state. The comparison of the main physicochemical parameters and enzymatic activity was carried out for the upper humus-accumulative horizons (0-30 cm). The relatively large scale of the study allowed to identify different stages of soil formation in fallow and re-involved soils. Soils were classified according to the international classification IUSS WRB (2022).

Table 1. Description of the studied soil profiles

Soil ID	Horizon*	Depth, cm	Description	Location	Coordinates	Soil name**
Ba1	E_1	4-10	Mineral horizon with features of loss of silicate clay and iron, light color	Benchmark forest, undisturbed soil	N58.832090 E30.153881	Stagnic Podzol (arenic)
	E_2	10-20	Mineral horizon with features of loss of silicate clay and iron			
Ba2	O_e	0-3	Organic material consisting brganic material consisting by moderate decomposed organic residues	120 years old fallow lands	N58.831588 E30.153031	Plaggic Podzol (arenic)
	A_p	3-28	Mineral horizon with the accumulation of humified organic matter			
Ba3	A_p	0-30	Mineral horizon with the accumulation of humified organic matter	80 years old fallow lands	N58.830129 E30.152454	Plaggic Podzol (arenic)
	B_s	30-70	Mineral horizon with illuvial accumulation of sesquioxides			
Ba4	A_p	0-30	Mineral horizon with the accumulation of humified organic matter	40 years old fallow lands	N58.831647 E30.150548	Plaggic Podzol (arenic)
	B_s	30-70	Mineral horizon with illuvial accumulation of sesquioxides			
B1	A_p	2-34	Mineral horizon with the accumulation of humified organic matter	20 years old fallow lands	59.305955 E30.118322	Plaggic Retisol (loamic)
	E	34-65	Mineral horizon with features of loss of silicate clay and iron			
B2	A_p	0-42	Mineral horizon with the accumulation of humified organic matter	Agriculture lands	N59.304304 E30.116394	Plaggic Retisol (loamic)
	B_t	42-70	Mineral horizon with illuvial accumulation of silicate clay			
B3	A/E	5-25	Transitional mineral horizon with features of accumulation of humified organic matter and loss of silicate clay	Benchmark forest, undisturbed soil	N59.302943 E30.119252	Retisol (loamic)
	B_t	25-50	Mineral horizon with illuvial accumulation of silicate clay			
Bor1	A_h	0-30	Mineral horizon with the accumulation of humified organic matter	Benchmark forest, undisturbed soil	N58.265268 E34.091997	Podzol (arenic)
Bor2	A_p	0-30	Mineral horizon with the accumulation of humified organic matter	30 years old fallow lands used as garden	N58.269883 E34.083628	Plaggic Podzol (arenic)
Bor3	A_p	0-30	Mineral horizon with the accumulation of humified organic matter	30 years old fallow lands, secondary forest	N58.268745 E34.085468	Plaggic Podzol (arenic)
Bor4	A_p	0-30	Mineral horizon with the accumulation of humified organic matter	30 years old fallow lands used as pasture	N58.269535 E34.083580	Plaggic Podzol (arenic)
Bor5	A_p	0-30	Mineral horizon with the accumulation of humified organic matter	30 years old fallow lands used as hayfields	N58.268671 E34.083279	Plaggic Podzol (arenic)
Bor6	A_p	0-30	Mineral horizon with the accumulation of humified organic matter	130 years old agriculture lands	N58.270034 E34.081949	Plaggic Podzol (arenic)

* Jahn et al. (2006) ; ** IUSS WRB. (2022)

The content of carbon and nitrogen was determined on CHN analyzer, pH was determined by potentiometric method. Particle-size distribution of soils was determined according to Bowman and Hutko (2002). The FAO recommended method (FAO, 2023) was used to estimate microbial activity, basal respiration (BR). The enzymatic activities (PHA, INV, URE and DHA) was determined by colorimetric method, CAT - gasometrically according to Galstyan's methods modified by Kazeev (Kazeev et al. 2012). The analog methods are presented in the work of Guan et al. (1986). During the analysis of urease, it was noted that its activity was below the measured level, therefore, it was not included in further calculations of total relative enzymatic activity. This is due to the low activity of urease in soils that have been subjected to anthropogenic influence relatively recently. The physicochemical parameters and enzymatic activity were analyzed in three repetitions.

To calculate the total relative enzymatic activity (TREA) (Kazeev et al., 2003) of soils, the maximum value of each of the indicators in the sample is taken as 100% and the value of the same indicator in the others samples is represented as a percentage relative to it (1):

$$\mathrm{B1} = \left(\frac{\mathrm{Bx}}{\mathrm{Bmax}}\right) * 100\% \tag{1}$$

where, B1 - relative score of the indicator;
Bx - actual value of the indicator;
Bmax - maximum value of the indicator.

The relative values of several indicators are then summarized. In this study: activity of the studied soil enzymes. Then the average evaluation score of the studied indicators characterizing an individual sample is calculated (2):

$$\mathrm{Bmean} = (\mathrm{B1} + \mathrm{B2} + \mathrm{B3} \ldots + \mathrm{Bn})/\mathrm{n} \tag{2}$$

where, Bmean - average evaluation score of indicators;
n - number of indicators.

TREA (3) is calculated similarly to formula (1):

$$\mathrm{TREA} = \left(\frac{\mathrm{Bmean}}{\mathrm{Bmean\ max}}\right) * 100\% \tag{3}$$

where, Bmean - average evaluation score of all indicators;
Bmean max - maximum evaluation score of all indicators.

Statistical processing of the data was performed in the Prism 10.2.2.397 software package (GraphPad software). The statistical test of two-way ANOVA ($p<0.0001$), Spearmen rank correlation ($p<0.1$), Pearson's correlation ($p<0.1$) as well as linear and nonlinear regression model (polynomial regression (2nd degree)) were used in this work. Linear and non-linear regression model was used for Ba2-Ba4 samples, due to the presence of different ages fallow lands, among which it is possible to conduct this analysis.

Results and Discussion

The features of soil formation on long-term fallowing lands

The vicinity of Ban'kovo village characterized by distribution of sandy parent materials by water-glacial origin and formation of podzol. In the studied 120-year-old podzol (Ba2) from Ban'kovo village the formation of transitional podzol horizon in the form of whitish layer, which is formed under the arable mineral humus-accumulative horizon, is noted. At earlier stages (80- and 40-year-old soils of fallow lands) this process is not pronounced. Formation of secondary podzol horizon is caused by change of plant communities from meadow to forest, formation of aggressive humus acids, destruction of mineral grains, which is accompanied by removal of iron and aluminum oxides and their accumulation in the middle horizon Bs.

For soils formed in the vicinity of Belogorka village (B1-B3), where the soil-forming rocks are represented by red-colored Devonian clays, more active rates of transformation are observed, in soils of fallow lands 20-years-old, formation of transition horizon with secondary eluviation is noted. The formation of this horizon is caused by excessive moistening in the boreal belt.

The studied soils in the Borovichi area are characterized by a long history of agricultural use, the area of ploughed land in this territory exceeded 80% during the Soviet period, and even those spruce forests that appear to be primary have been subjected to a very significant anthropogenic impact. The soils of the Bor2-Bor4 have loose initial E and Bs horizons, hence they were involved in arable horizons during Soviet times and show no signs of degradation during the following thirty years. Only the soil under the hayfield (Bor5) has some signs of degradation as follow secondary podzolization in the old arable horizon. Soils of agricultural lands can be subjected to significant changes as a result of transition to fallow state, this is caused by the change of plant communities, waterlogging, loss of organic matter and transformation of soils towards zonal series (Kalinina et al., 2019). The studied soils in the area of Ban'kovo village are less subject to transformation, this is due to the features of soil formation on red-colored sandy moraine sediments, on which the process of secondary podzolization can take more than 300 years (Litvinovich, 2009).

The studied soils are characterized by different degree of fallow state and type of agricultural use, which allows to study temporal and spatial dynamics of enzymatic activity.

Physico-chemical characteristic of studied soils

The studied undisturbed soils (Ba1, B3, Bor1) are characterized by acidic reaction, with relatively high content of carbon represented in the form of coarse forms of humus. Relatively high pH value was characterized by soils (Bor2-Bor6) in the area of Borovichi, which is associated with the young age of transition to fallow state, as well as their use in the form of gardens, pastures, and for growing crops. Soils of fallow lands were characterized by a higher pH level, indicating that agricultural influence has a long-term effect on the soil and does not contribute to a sharp change in the acid-base balance of soils (Table 2). However, according to Litvinovich (2009) fallow soils formed on water-glacial and lake-glacial sediments can change acidity relatively rapidly, which is due to active leaching processes and migration of Fe and Al oxides. In the first three decades, soils of fallow lands can retain their acid-base properties even if fertilizer application is stopped (Dymov et al., 2018).

Table 2. Physico-chemical parameters of studied soils.

Soil ID	Horizon	pH	C, %	BR, mgCO$_2$-C/g h^{-1}	N-NH$_4^+$	N-NO$_3^-$	P	K	Sand	Silt	Clay
					mg/kg				%		
Ba1	E$_1$	4.98	4.98	0.25	3.88	0.36	29	25	92	4	4
	E$_2$	5.91	5.91	0.19	2.83	0.36	188	16	86	11	3
Ba2	O$_e$	5.58	4.70	-	9.43	2.12	205	28	88	7	5
	A$_p$	5.64	1.39	1.66	2.46	0.45	140	23	90	6	4
Ba3	A$_p$	5.68	0.62	1.63	1.36	0.36	222	505	93	4	3
	B$_s$	5.71	0.35	1.03	1.31	0.06	187	264	93	3	4
Ba4	A$_p$	5.89	1.44	1.44	1.10	0.36	276	397	89	7	4
	B$_s$	5.85	0.38	0.63	0.68	0.18	106	522	90	7	3
B1	A$_p$	4.87	1.44	0.09	4.45	1.84	210	103	70	24	6
	E	5.25	0.62	0.06	0.68	1.60	43	107	67	25	8
B2	A$_p$	5.69	1.48	0.45	5.97	6.32	255	470	72	22	6
	B$_t$	5.66	0.53	1.05	1.15	1.54	125	264	69	15	16
B3	A/E	4.42	2.28	1.28	3.09	0.33	19	692	78	17	5
	B$_t$	4.79	0.82	0.34	1.83	0.45	241	560	75	19	6
Bor1	A$_h$	5.73	0.83	0.82	4.08	0.27	25	10	88	5	7
Bor2	A$_p$	6.11	1.40	0.05	6.49	0.49	59	13	75	18	7
Bor3	A$_p$	6.67	2.55	2.03	11.78	1.06	70	69	77	16	7
Bor4	A$_p$	6.37	2.42	1.60	11.52	2.31	161	195	86	11	3
Bor5	A$_p$	6.23	2.21	1.45	7.91	0.70	93	93	85	10	5
Bor6	A$_p$	6.87	3.77	1.27	5.92	3.61	499	505	83	11	6

Based on the data on carbon content in soils of fallow lands, we can note that the highest carbon content corresponds to Plaggic Podzol formed in the vicinity of Borovichi city. This is due to the different type of land use, development of humus-accumulative process, as well as fertilizer application. Soils of fallow lands, which are in the process of long-term self-restoration, are characterized by the formation of litter horizon (Ba2 O$_e$), in which weakly decomposed plant residues are accumulated. This horizon is formed above the old arable horizon. Younger variants of fallow land soils are characterized by the presence of old ploughing horizon from the surface, in which humus accumulation and transformation takes place, the carbon content in them varies in a wide range from 0.62% in Ba3 A$_p$ horizon with the age of 80-years-old to the highest carbon content of 1.48% in B1 A$_p$ horizon with the age of 20-years-old. Soils that had not recently come out of agricultural influence were characterized by the highest carbon content 40-years-old (Ba4 1.44% carbon content) as well as 20 years old (B1 1.48%). Regression analysis was performed to identify the relationship between the content of carbon and biogenic elements in old-arable soil horizons and the age of the deposit (Figure 2).

The obtained model shows that for this site the minimum of carbon content (Figure 2A) is observed between 80-81 years, after this time there is an increase in carbon content in the old-arable horizon. This may be due to active accumulation of organic matter as a result of transformation of plant residues that accumulate in the overlying O horizon.

Based on the analysis of basal respiration in soils, it was noted that the highest level is observed in old ploughed humus-accumulative horizons (Ba3, Ba2), where active transformation of organic matter takes place. Younger fallow soils were characterized by lower values of basal respiration.

From distribution of N-NH_4^+ it was noted that the highest content of ammonium form of nitrogen is characteristic of secondary forest plots (Bor3), as well as pasture (Bor4), fallow soils not used in agriculture were characterized by significantly lower content of N-NH_4^+, which may be associated with the cancellation of mineral fertilizer application. According to the obtained regression model (Figure 2E) for the Ban'kovo site, the N-NH_4^+ content was found to increase significantly with the age of the fallow state.

The highest content of N-NO_3^- was observed in the soil used in agriculture (B2), which is due to the application of mineral forms of fertilizers to the soil. The same is followed for phosphorus in the soil, the highest content was observed in the soil of agricultural land (Bor6). At the same time the lowest content of this element was found in horizons of undisturbed soils (Ba1 E_1, B3 A/E). According to the linear regression model (Figure 2D) for the Ban'kovo site, it was found that N-NO_3 content increases with age.

The highest content of potassium was noted in undisturbed soil B3 A/E, which is due to its relatively high content in soil-forming rocks. The distribution of potassium (Figure 2C) as a function of time for the Ban'kovo site is described by a nonlinear polynomial regression of the second degree, which shows that the maximum of potassium content falls on 65-70 years, after this time there is a decrease in the content. Phosphorus is characterized by a decrease in content with increasing age of the deposit, which is described by a linear regression equation (Figure 2B). According to the data of particle-size distribution, most of the studied soils belong to sands and sandy loam, except for soils formed in the area of Belogorka village (B1-B3), here the content of sand decreases and the content of dusty and clay particles increases, which is due to the formation of soils on deposits of Devonian red-colored clays.

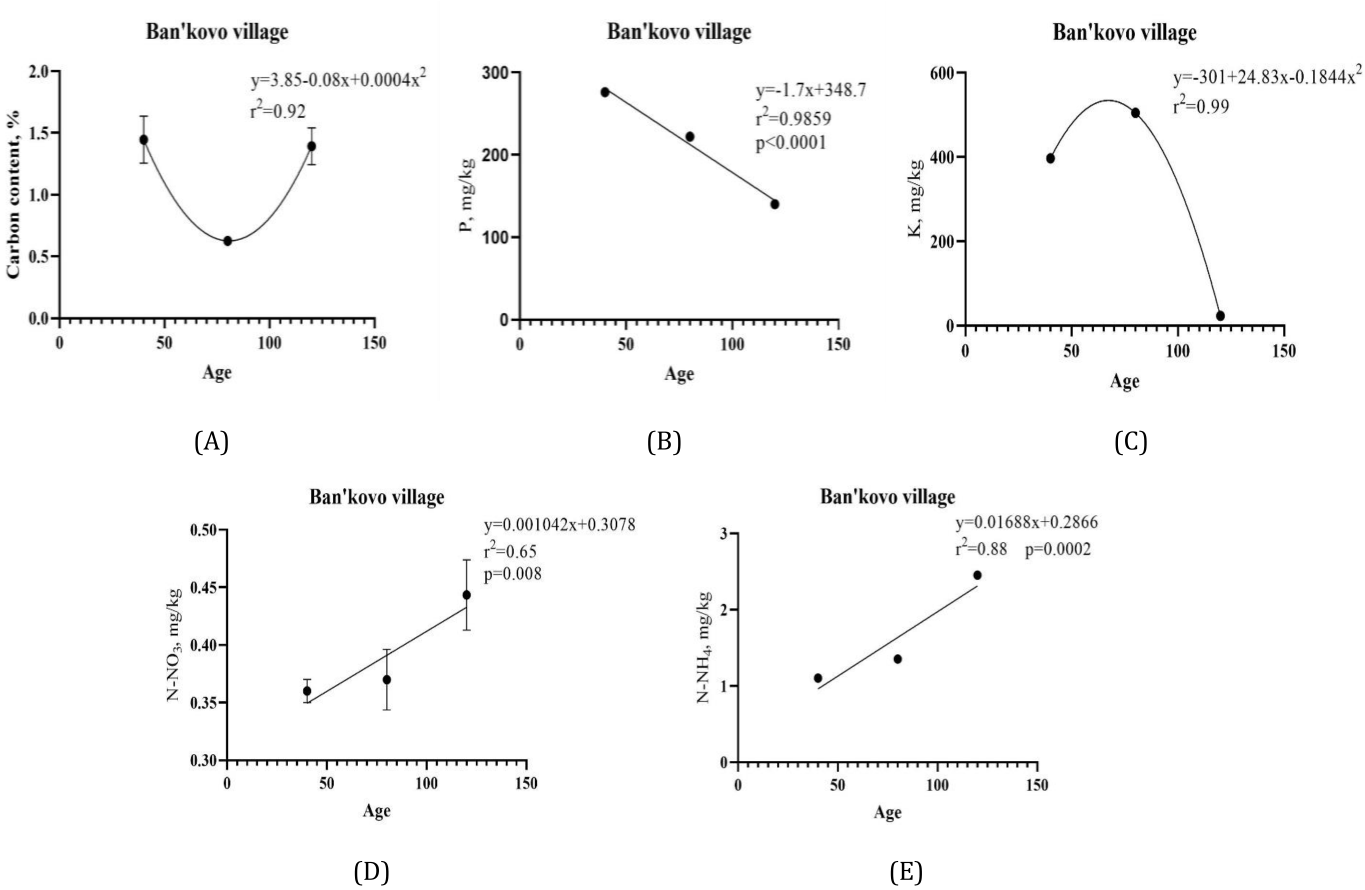

Figure 2. Changes in carbon and biogenic elements content depending on the period of their abandonment. A – carbon content (%), B – P, mg/kg, C – K, mg/kg, D – N-NO_3, mg/kg, E – N-NH_4, mg/kg.

Spearman rank correlation analysis was applied to identify the correlation between the investigated physico-chemical parameters (Figure 3).

According to the obtained data, we can note that there is no high correlation among the studied parameters except for the content of sand and dust. This is due to the different age of soils of fallow lands and features of soil transformation in the conditions of transition to fallow state.

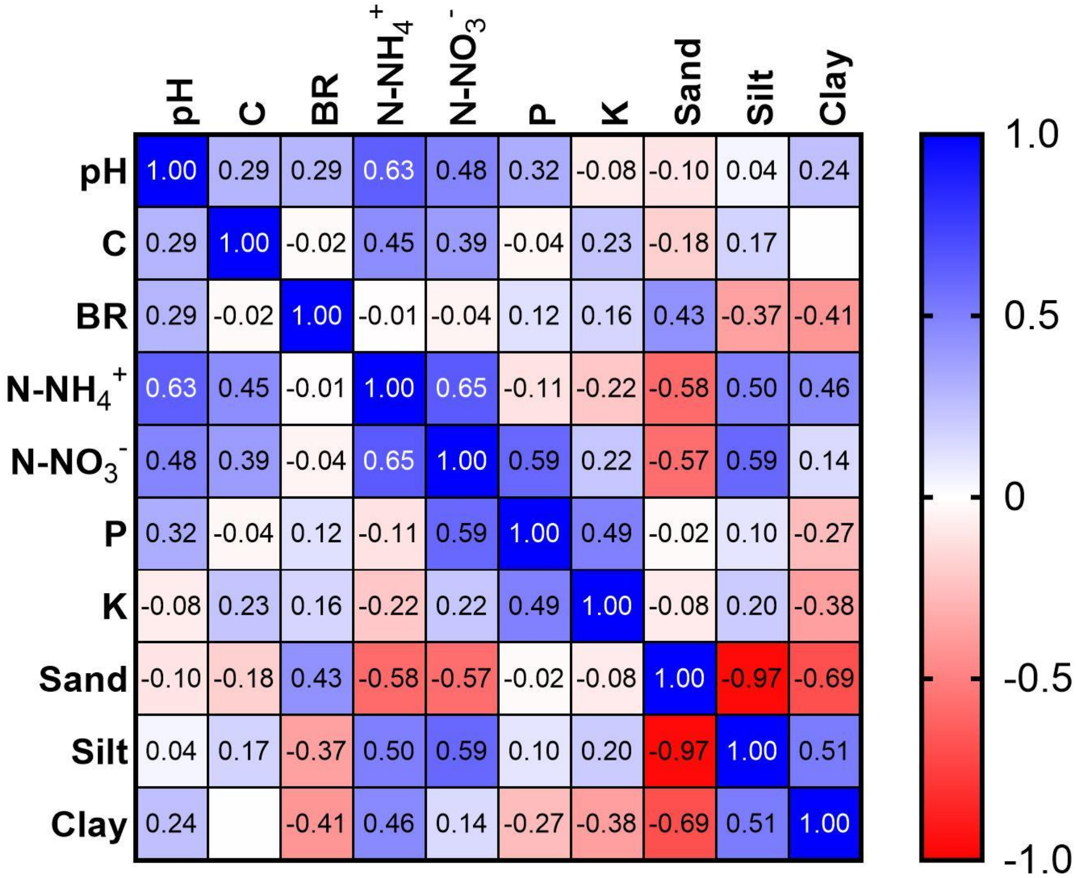

Figure 3. Spearman rank correlation graph for physico-chemical parameters of soils.

Enzymatic activity of soil

To characterize the enzymatic activity of soils of fallow land as well as soils with different types of use, the catalytic activities of enzymes of hydrolase (INV, PHA, Ure) and oxidoreductase (DHA, CAT) classes were studied (Figure 4, 5). According to the data obtained, the enzyme activities of soils have high variability Cv ranges from 68.13% for DHA to 220.9% for Ure. The high variability of these enzymes has been noted by other researchers (Gorobtsova et al., 2017), who attribute this with the high variability of soil formation conditions, anthropogenic impact, as well as the time of soils being in fallow state. According to the statistical analysis, significant differences ($p<0.0001$) in enzyme activity among the upper humus-accumulative horizons of the studied soils were determined.

Among the enzymes of hydrolase class, the highest activity was observed for PHA, for Bor6 (159.48 mgP_2O_5/100 g/1 h) in agricultural soils. The high activity of PHA in agricultural soils was due to the application of mineral forms of phosphorus. In fallow soils, PHA activity decreased with the age of transition to fallow state, with very strong activity in undisturbed soils (Ba1 E_1, B3 A/E). The high PHA activity in undisturbed soils may be due to active transformations of organo-mineral components in podzol horizons (E). According to the Ure activity, it was found that no Ure activity was observed in most of the studied soils. The highest activity was observed in secondary forest (Bor3), as well as in Ba2 O_e, thus Ure activity is associated with the formation of forest litter on fallow land soils. Similar results were obtained in a study on enzyme activity on secondary forests formed in place of fallow land conducted in China's Danxia Province, which showed that reclaimed land contained more hydrolytic enzymes than arable soils (Wang et al., 2023). According to the data obtained during the analysis of INV activity it was noted that the highest activity level was observed in soils of different types of use Bor4 (pasture), Bor3 (secondary forest), Bor2 (garden), as well as soil used in agriculture (Bor6). Among soils of fallow lands, it can be noted that INV activity was higher in old-aged fallow soils (Ba2 O_e) and decreased with decreasing age of transition to fallow state.

DHA activity was found to be very weak in most of the studied soil samples, the highest activity was observed in Ba2 O horizon (5.83 mgTFF/10 g/24 h). Our data are confirmed by Gorobtsova (2017), who found that in undisturbed horizons DHA activity is higher than in arable horizons. DHA activity depends significantly on the type of land use, as well as on the quality of organic matter, the content of labile forms of humus leads to an increase in DHA in soils (García-Ruiz et al., 2008). CAT activity averaged 1.35 mgO_2/1 g/ 1 min, and was weak in most of the studied samples, the average activity level was recorded in sample Bor 3 (secondary forest). The activity level decreased from undisturbed soils to fallow soils. The activity of oxidoreductases was higher in soils with restoration of woody vegetation species and in soils with formation of litter horizon O, where transformation of plant residues takes place.

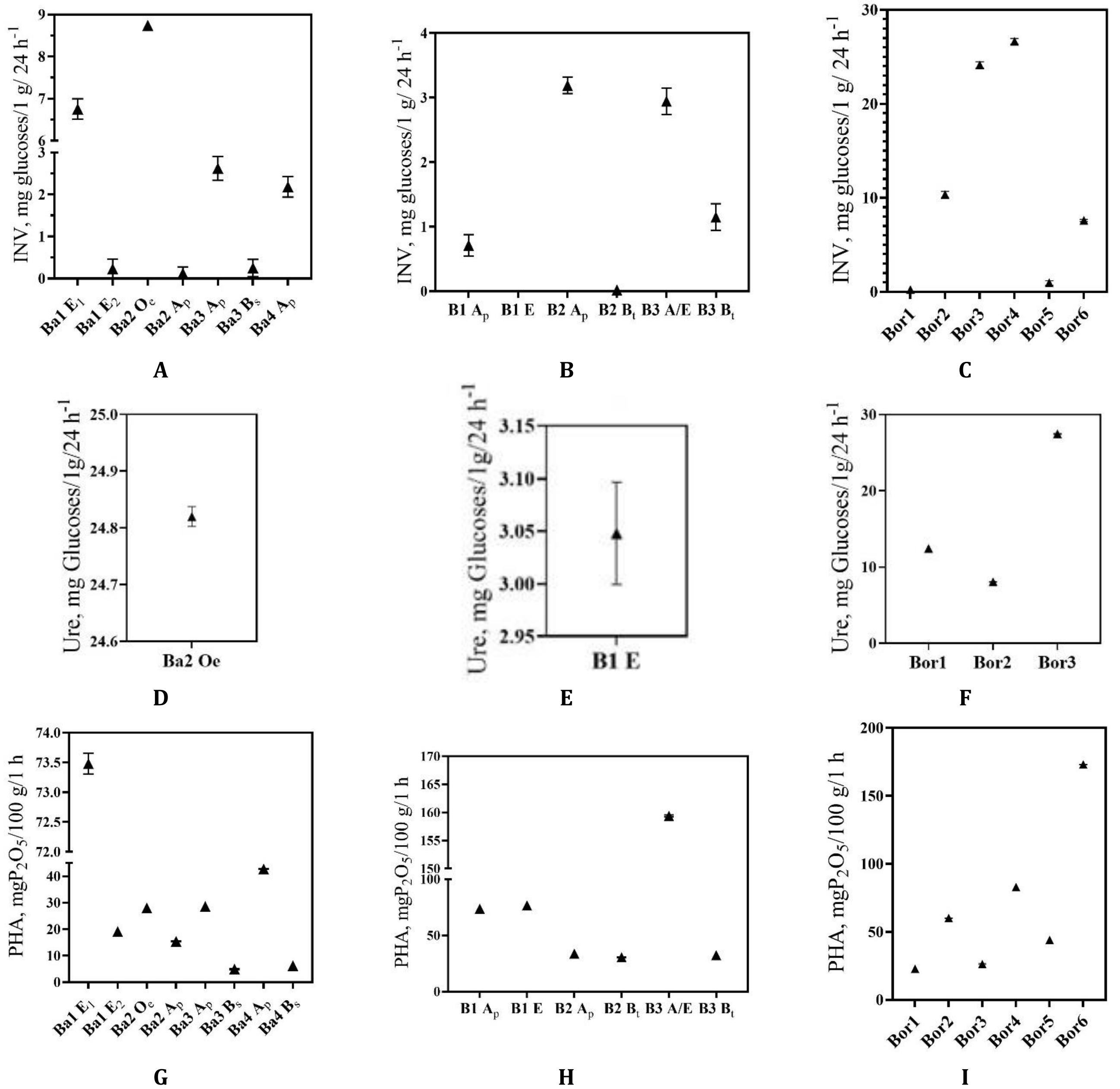

Figure 4. Soil enzymatic activity indices (INV, Ure, PHA) of undisturbed and fallow lands, as well as lands with different types of use (p<0.0001). A, D, G – Ban'kovo, B, E, H – Belogorka, C, F, I - Borovichi

Pearson's correlation was performed to analyze the correlation relationship between physicochemical parameters of soils and enzymatic activity. It was found that for $N\text{-}NH_4^+$ content has a high level of correlation with INV ($r=0.84$, $p<0.0001$) and with CAT ($r=0.82$, $p<0.0001$). It is observed that clay content has a relatively high level of correlation with DHA ($r=0.66$, $p=0.01$) and URE ($r= 0.61$, $p=0.02$). Figure 6 shows the dependence of enzymatic activities on physicochemical parameters of soils.

The comparison of the studied soils shows that almost all enzymes at all studied sites lost their activity down the soil profile, which is in accordance with the results of other researchers (Gorobtsova et al., 2015).

To identify the total biological activity of the studied soils, the total relative enzymatic activity was calculated according to Zvyagintsev (1978) and Kazeev (2003) and used in the works of Gorobtsova (2015). Two enzymes from the hydrolase class (phosphatase and invertase) and oxidase class (dehydrogenase and catalase) were used in the calculation of total relative enzymatic activity in this work. The activity of Urease was not included in the calculation because at most points, it showed no activity. The Figure 7 presents diagrams showing the total relative enzymatic activity of the upper horizons of soils in the studied plots. The obtained data show that in the area of Bankovo village the total enzymatic activity of soils increases when the period of fallow state from 40 to 120 year increases. The increase in enzyme activity in the process of postagrogenic evolution is also mentioned in the work (Kazeev et al., 2020). It shows that enzyme activity starts to increase in the first year of fallow state and continues to recover throughout the time after the cessation of agrogenic impact.

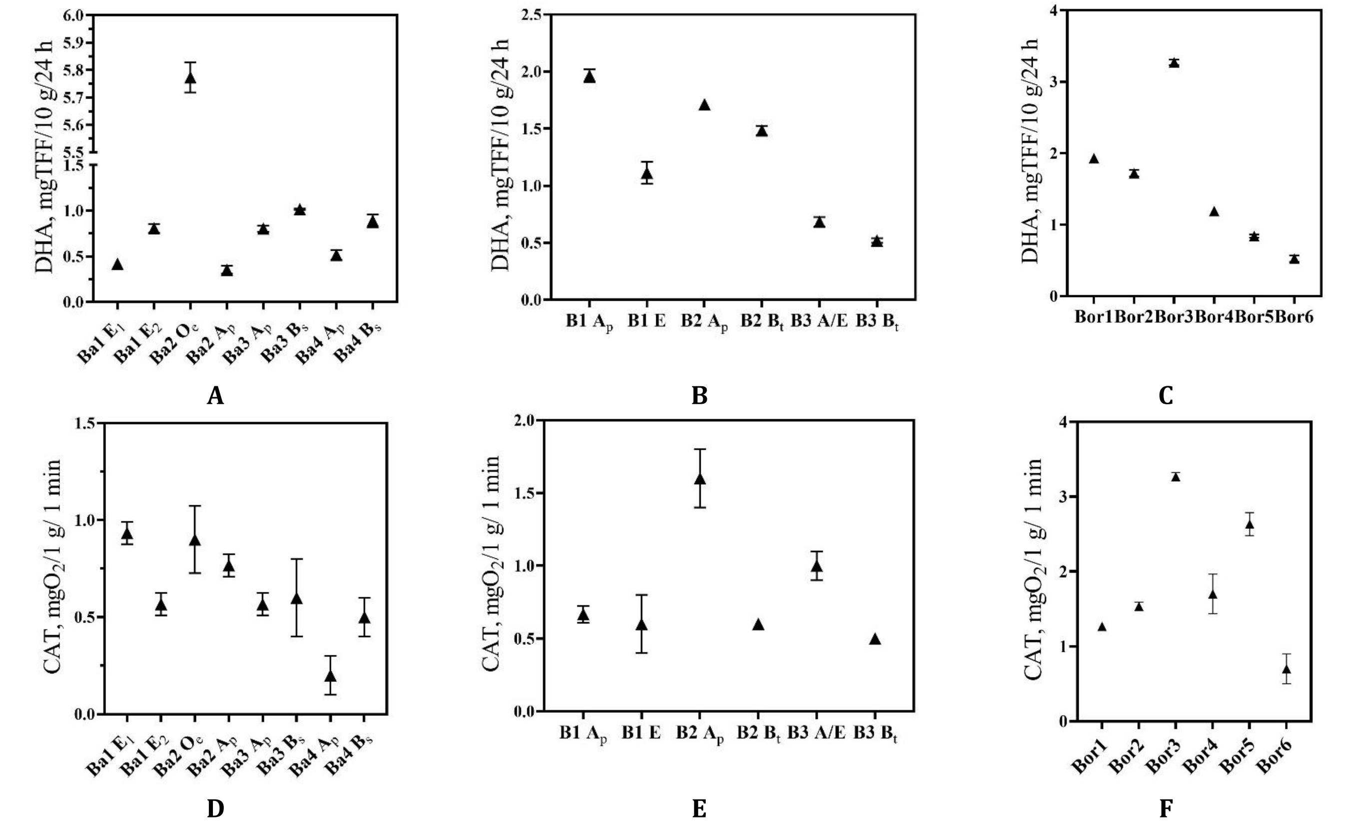

Figure 5. Soil enzymatic activity indices (DHA, CAT) of undisturbed and fallow lands, as well as lands with different types of use (p<0.0001). A, D – Ban'kovo, B, E – Belogorka, C, F – Borovichi.

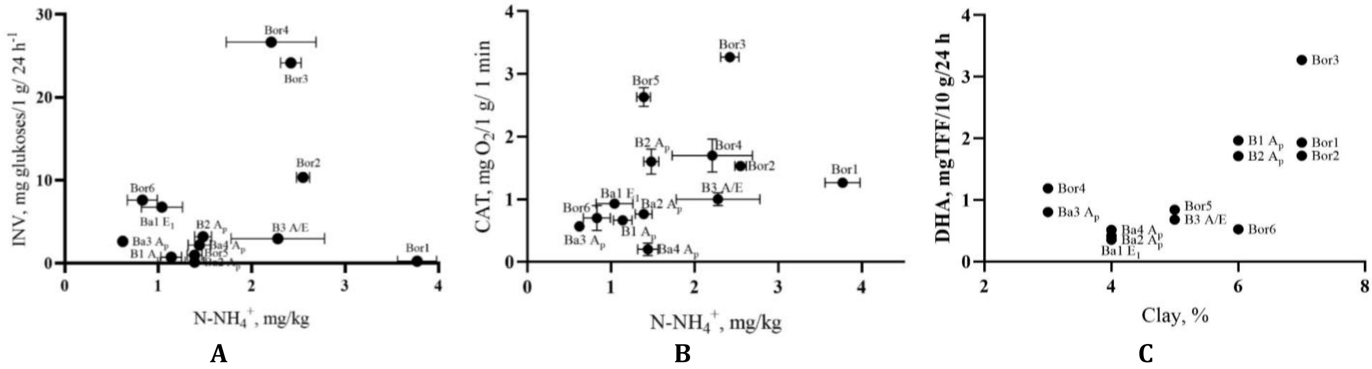

Figure 6. Relationship between physico-chemical parameters and enzymatic activity. A - Relationship between $N\text{-}NH_4^+$ and INV. B - Relationship between $N\text{-}NH_4^+$ and CAT. C - Relationship between Clay and DHA.

In comparison with the soils in the Bankovo area, in the soils formed in the vicinity of Belogorka village, the total enzymatic activity in the soils of agricultural land is higher than in the soils under 20-year fallow land. Such a high value of total enzymatic activity in arable soil was obtained due to high values of redox enzymes. Similar results were obtained in the study of fallow soils in Belgorod region (Ovsepyan et al., 2017), which revealed higher activity of redox enzymes in arable soils compared to fallow soils. Comparison of the total enzymatic activity of 30-year-old fallow soils under different land uses in the Borovichi area revealed that soils under secondary forest had the highest biological activity. The lowest values of total enzymatic activity in this area were found in the undisturbed soils under forest (Bor 1). This is probably due to the fact that the soil in this area is acidic, which is consistent with studies (Gedgafova et al., 2015; Gorobtsova et al., 2015) showing that enzyme activity is higher in soils with slightly alkaline reaction compared to acidic soils.

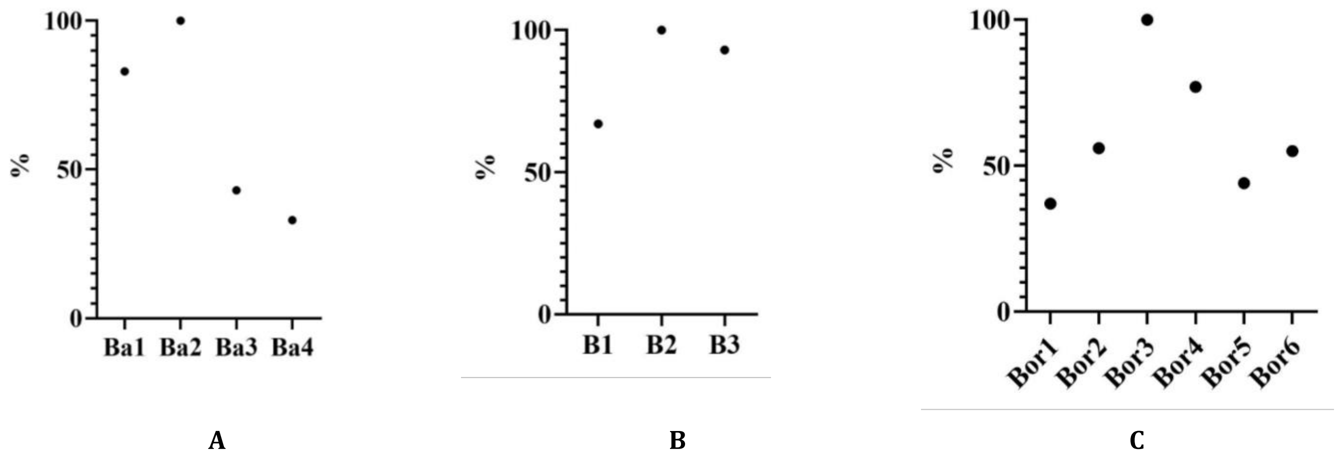

Figure 7. Total relative enzymatic activity (%) of the surface soil layer of the study sites.
A – Ban'kovo, B – Belogorka, C – Borovichi.

Comparison of all studied plots showed that the soil under the secondary forest formed on a 30-year fallow land has the highest total enzymatic activity. High biological activity at this site is due to the neutral pH, some of the highest values of organic carbon and nitrogen content, and basal respiration, which according to various authors (Kazeev et al., 2004; Gorobtsova et al., 2015) have a positive correlation with the total enzymatic activity of soils.

Conclusion

The transition of agricultural soils to fallow state induces complex changes in their biochemical and physicochemical properties. As soils remain uncultivated, several key transformations occur: pH gradually decreases due to natural podzol formation processes and shifts in vegetation cover, leading to the formation of E horizon and leaching of sesquioxides. The dynamics of biogenic elements follow a U-shaped pattern - initial depletion in early fallow stages gives way to gradual accumulation as the ecosystem stabilizes. Enzymatic activity undergoes significant modifications reflecting these ecological changes. Urease, dehydrogenase and catalase activities peak in mature soils of fallow lands, suggesting microbial communities retain memory of past agricultural use. Phosphatase shows maximal activity in arable soils due to residual effects of phosphorus fertilization. Invertase shows the most variable response, with highest activity observed across different land-use types, particularly in mature fallow systems.

The most biologically active soils are found in 30-year fallows state that have developed secondary forest cover. These systems combine neutral pH, high organic carbon content, and basal respiration, which is forms optimal conditions for enzymatic processes. Total enzymatic activity in such ecosystems often exceeds that of both recently abandoned fields and continuously cultivated lands. These patterns demonstrate that fallow succession drives non-linear changes in soil enzymatic profiles. Early fallow stages typically show low activity, while mature systems close or exceed the biological activity of native ecosystems.

Further research should focus on long-term monitoring of enzyme dynamics across different soil types and climatic zones to better predict fallow system recovery.

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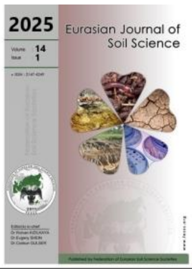

Agronomic efficiency of fertilization in triticale cultivation

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Abstract

The present study aims to investigate how fertilization levels impact the partial factor productivity of nitrogen, phosphorus, and potassium in triticale. The experiment was set up in four repetitions on the experimental field of the Agricultural University of Plovdiv for three years after the predecessor sunflower. The field trial included three triticale varieties: Kolorit (standard), Trismart, and Musala grown at two fertilization levels $N_{60}P_{50}K_{20}$ and $N_{120}P_{100}K_{40}$. Fertilization levels significantly affected the partial productivity values of nitrogen, phosphorus, and potassium, either separately or in total, regarding the productivity of grain and grain protein in the three triticale varieties. The average partial productivity of nutrients over the study period decreased as the level of fertilization increased. For each unit of nutrients applied, less grain or grain protein was produced at higher fertilizer rate compared to a lower one. Specifically, the results from the double fertilization rate of $N_{120}P_{100}K_{40}$ showed that the efficiency of each kilogram of nutrient imported was lower. The average partial productivity of applied PFP-NPK nutrients was higher at the low $N_{60}P_{50}K_{20}$ fertilization level. The climatic conditions during the triticale vegetation had a significant effect on the partial productivity of nitrogen, phosphorus, and potassium for grain yield. The lowest values of the partial productivity were found in the variety Trismart grown at $N_{120}P_{100}K_{40}$ level in the unfavourable climatic 2017. The productivity of all three elements was highest in the variety Musala, fertilized with $N_{60}P_{50}K_{20}$ in 2019. Unfavourable conditions in 2017 reduced the partial productivity of nitrogen for grain by 40.0 kg kg^{-1} at the level of $N_{60}P_{50}K_{20}$ and by 15.6 kg kg^{-1} at $N_{120}P_{100}K_{40}$. Drought resulted in lower grain production per unit of phosphorus and potassium applied.

Keywords: Agronomic efficiency, fertilization, partial productivity, triticale.

Introduction

As food insecurity increases, enhancing the efficient use of water and nutrients has become a critical area of research (Fixen et al., 2015). The efficiency of farming systems is calculated as the ratio of revenues to system inputs and can be determined in different ways depending on the specific interest (Norton et al., 2015). The most used indices directly related to the use of fertilizer elements are four: partial productivity of the PFP element, agronomic efficiency AE, partial nutrient balance PNB, and recovery efficiency RE (Fixen, 2015). Two of the indices—partial productivity and agronomic efficiency—determine productive efficiency, where revenues are the primary output. The other two indices—partial nutrient balance and recovery efficiency—characterize return efficiency, reflecting how effectively plants utilize applied nutrient elements from fertilizers. The partial productivity of nutrients (PFP) resulting from fertilization evaluates the productivity of a system concerning the nutrients added. This index provides a simple way to measure yield efficiency and is calculated by dividing the crop yield by the amount of applied nutrients. The most important aspect for farmers is the ability to integrate the efficiency of elements from both the soil and applied fertilizers. It serves as a long-term trend indicator (Fixen et al., 2015). Two important conclusions

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have been drawn when studying and analyzing the effectiveness of nutrients worldwide. The efficiency of fertilization observed in research trials is greater than what is achieved in real farm conditions. Additionally, the existing data on current fertilizer usage is inadequate for various crops, farming systems, and regions. While many technologies have been developed to enhance the efficiency of fertilizers, their adoption by farmers remains significantly low (Murrell, 2011). In recent years, nutrient application on arable land has improved crop yields and increased societal understanding of nutrient efficiency (Salim and Raza, 2019). Especially in unfertile soils the crop production systems depend on nutrient supply (Salim and Raza, 2019). Moreover, precise agriculture management practices enable the application of nutrients at the proper time and rate (Salim and Raza, 2019).

In 2023, according to FAO, production areas with triticale amounted to almost 4 million ha. (FAOSTAT, 2023). The main reason for the great popularity of triticale is the high and stable productivity in a poor nutritional regime, as well as the resistance to diseases, enemies, and adverse environmental factors (Feledyn-Szewczyk et al., 2020, Jańczak-Pieniążek, 2023). Crop productivity is influenced by various factors. These include advancements in cropping systems, the application of production inputs such as high levels of nitrogen fertilization, and effective crop protection methods. Additionally, the distribution of precipitation throughout the growing season and the efficiency of nitrogen use play crucial roles in determining crop yields (Taiz, 2013, Iizumi and Ramankutty, 2015, Sirakov et al., 2021). Fertilizer application aims to bring the yield closer to the standard values and even exceed them (Gaj et al., 2023). In most cases, the amount of fertilizers introduced to obtain the planned yield is greater than the actual quantity of nutrients that the culture needs (Gaj et al., 2023). Plant assimilation, substrate absorption, ammonia volatilization, and denitrifications are among the possible ways to remove excess nitrogen from the soil (Wang and Xing, 2016). Sustainable fertilization practices require a combined approach to increase productivity while respecting soil health and protecting the environment (Erisman et al. 2018).

This study aims to determine the effect of fertilization level on the partial factor productivity of nitrogen, phosphorus, and potassium on triticale.

Material and Methods

Experimental setup

The experiment was performed at the experimental field of the Agricultural University of Plovdiv, Bulgaria (42°9' N, 24°45'' E, 160 m altitude) during the period 2016-2019 under non-irrigated conditions. The field trial included triticale varieties Kolorit (standard), Musala, and Trismart, created in different breeding centers and grown at two fertilization levels: $N_{60}P_{50}K_{20}$ and $N_{120}P_{100}K_{40}$. The experiment was set according to the block method in 4 repetitions with a test area of 15 m^2 after the predecessor sunflower. The fertilization with the triple superphosphate (46% P_2O_5) and potassium chloride KCl (60% K_2O) took place pre-sowing before the first soil cultivation, and nitrogen in the form of ammonium nitrate NH_4NO_3 (34% N) was applied once in early spring. Sowing was carried out within the appropriate agrotechnical period (depending on the conditions in the autumn and a sowing rate of 550 germinated seeds/m^2). Weed control was consistent with the level of weeding conducted in the respective spring. The herbicide Acurat 60 WG (Metasulfuron-methyl) was applied at a dose of 10 g ha^{-1} to target annual and perennial broadleaf weeds during the tillering phase.

At maturity, the total nitrogen concentration of triticale grain was determined using the Kjeldahl method, following wet digestion with H_2SO_4 and H_2O_2 as catalysts (Tomov et al., 2009). The grain protein concentration was calculated from the grain nitrogen percentage multiplied by a coefficient of 5.6 (Mariotti et al., 2008). The grain protein yield, measured in kilograms per hectare (kg ha^{-1}), was calculated using the following formula: (Grain yield in kg.ha^{-1} multiplied by the percentage of protein in the grain) / 100.

The partial productivity of applied nutrients (N, P_2O_5, K_2O, or total NPK) was calculated based on grain yield and triticale grain protein yield. This was expressed as the ratio of grain yield (or grain protein yield) to the amounts of nitrogen, phosphorus, and potassium applied through fertilizers, as described by Dobermann (2007).

Partial factor productivity (PFP), kg kg^{-1} = Grain or Protein yield in kg ha^{-1} / Fertilizer rate of N, P_2O_5, K_2O, NPK in kg ha^{-1}.

Soil characterization

The experiment was conducted on alluvial-meadow soil *Mollic fluvisols*, the weakly solonetz, with a power of horizon A 25 – 28 cm (Popova et al., 2012). The soil is medium sandy loam with a physical clay content in the A horizon of 33%. The soil contains a moderate amount of calcium carbonate, which gives it better physico-chemical and aquatic properties. The reaction of the soil is slightly alkaline with an average value of 7.80 in the 0-30 cm layer and 7.70 in the 30-60 cm layer (Popova et al., 2012). The cation sorption capacity and the degree of base saturation are relatively high (20-30 mequ/100g and 90-92%, respectively). The content of organic matter is 1.3% (Popova et al., 2012). The content of mineral nitrogen and available phosphorus and potassium in the soil before sowing of the triticale was determined in soil layers 0-30 and 30-60 cm (Table 1). The results show that the soil was poorly stocked with mineral nitrogen, well stocked with mobile phosphorus, and very well stocked with absorbable potassium.

Table 1. Content of mineral nitrogen and mobile forms phosphorus and potassium before sowing triticale.

Year	0-30 cm			30-60 cm		
	Nmin, mg kg^{-1}	P_2O_5, mg/100 g	K_2O, mg/100 g	Nmin, mg kg^{-1}	P_2O_5, mg/100 g	K_2O, mg/100 g
2016	25.9	25.8	41,3	20.7	19.9	34.0
2017	30.2	27.3	43.2	23.5	21.1	32.6
2018	24.7	26.9	51.1	19.3	22.8	34.4

Weather conditions

The study was conducted in an experimental field located in the transitional Mediterranean climatic sub-region of the European-continental region of Bulgaria. This agroclimatic region is characterized by warm springs and autumns, which are relatively short. The average annual temperature does not fall below 13 °C, and the annual temperature amplitude does not exceed 23^0 C. The highest rainfall occurs in early summer, during May and June, while a minimum of precipitation is recorded in early autumn, in August and September (Peev and Kouzmova, 2002). The hydrothermal conditions during the three vegetation periods of the triticale are presented in Figure 1. Their analysis points out that the first experimental year differs from the average multiannual average. The autumn drought delayed the germination phase, and the air temperature was close to the minimum temperatures for the growth and development of triticale. January was characterized as cold, and the average monthly temperature (-3.9°C) was lower than the climate average. Typical for this month were the sharp and short-term decreases in temperatures to - 10.3°C and the lack of snow cover, which posed a real threat to the crop, but despite the low temperatures, no frost has been recorded. The total amount of rainfall during the vegetation of the triticale is 271.6 mm below the climate average of the region. The second experimental year was characterized by a sum of the average monthly temperatures exceeding the climate average by 2.1 °C. A sufficient amount of precipitation contributed to a better moisture supply of the soil and the optimal development of the triticale. Hydrothermal conditions in the third year were similar to the second year, with positive temperatures in the autumn-winter period exceeding the multiannual period.

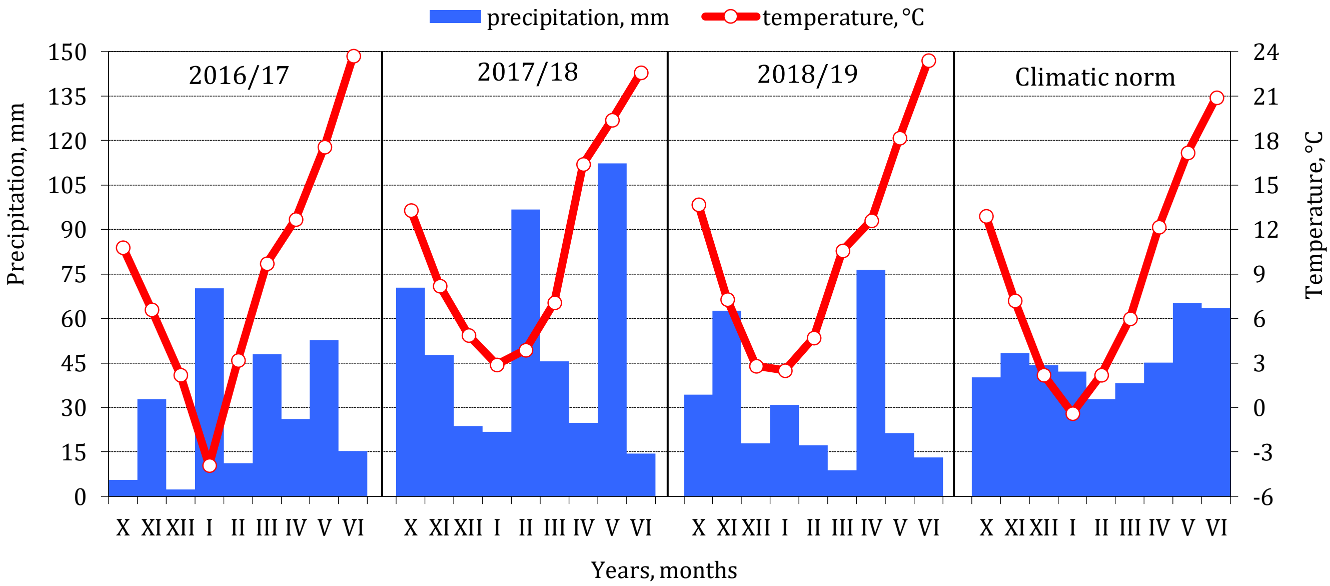

Figure 1. Climatogram during triticale vegetation.

Data Analysis

For statistical data processing one way ANOVA and Duncan's multiple range test (P = 0.05) were used to find significant differences among means. The Pearson correlation coefficient was determined with XLSTAT Version 2016.02.

Results and Discussion

The fertilization level has a proven positive effect on the yield of grain and grain protein from triticale. The result of the higher fertilization level $N_{120}P_{100}K_{40}$ is an increase in the average grain and grain protein yield of the varieties by 42.0 % and 72.1 %, respectively (Tables 2 and 3). The productivity of the three varieties varies widely, and no proven varietal differences have been found on average over the three years. The grain yield varies from 2013 kg ha^{-1} (variety Kolorit at level $N_{60}P_{50}K_{20}$ in 2017) to 6622 kg ha^{-1} (variety Musala at level $N_{120}P_{100}K_{40}$ in 2019). In terms of grain protein yield, the lowest value of 128.2 kg ha^{-1} was obtained by the variety Trismart fertilized with $N_{60}P_{50}K_{20}$ in 2017, and the highest yield of 445.5 kg ha^{-1} was obtained from the variety Musala at the level of $N_{120}P_{100}K_{40}$ in 2019. The influence of climatic conditions during the vegetation on the productivity of triticale is significant. In 2017, the grain yields were at their lowest values due to unfavourable conditions. However, in the following two years, the improved conditions resulted in a significant increase in yields, with nearly a twofold rise in 2019 compared to 2017. It is known that the yield of grain protein from triticale determines the nutritive value of the feed and the use of the crop as a raw material for the livestock industry. The influence of climatic factors has been demonstrated in the present study. At the low fertilization level $N_{60}P_{50}K_{20}$, less grain protein was obtained from triticale in 2017 than protein yields in 2018 and 2019. With increased fertilization $N_{120}P_{100}K_{40}$, significant differences were observed between the obtained grain protein yields in the 2017 and 2019 harvest years, while the protein yield in 2018 did not differ significantly from that of 2017 and 2019. Other authors have also confirmed mineral nutrition's positive effect on the triticale grain's protein content (Jaśkiewicz and Szczepanek, 2018; Hospodarenko and Liubych, 2021; Muhova et al., 2024). The same researchers reported a significant effect of the weather conditions during the growing season on the nitrogen-containing compounds in triticale grain. Those results also correspond to the findings of Lalević et al. (2019). Lestingi et al. (2010) reported that a small input of nitrogen of 50 kg ha^{-1} instead of 100 kg ha^{-1} ensured a good productivity and quality of the triticale grain. By changing the input conditions from low to optimum triticale grain performance increases by 68% (Vats et al., 2016). The same authors reported that triticale responded differently to mineral nutrition depending on the genotype. According to Knapowski et al. (2009), increased nitrogen rates between 80 and 120 kg ha-^{1} led to a 9.6% increase in triticale productivity. Janušauskaitė (2013) observed that a nitrogen rate of 90-120 kg ha^{-1} is optimal in economic terms for achieving high yields from spring triticale. Many researchers (Cimrin et al., 2004; Mut et al., 2005) confirmed the positive effect of higher nitrogen rates on triticale. According to Mut et al. (2005) triticale can use very high doses of nitrogen.

Table 2. Grain and grain protein yields of triticale depending on the fertilization level and cultivar.

Year	2017	2018	2019	Average	2017	2018	2019	Average
Fertilization		$N_{60}P_{50}K_{20}$				$N_{120}P_{100}K_{40}$		
Grain yield, kg ha^{-1}								
Kolorit	2013	4028	4604	3548^{ns}	3925	5472	5842	5080^{ns}
Musala	2161	4803	5301	4088	4419	6223	6622	5755
Trismart	1989	3856	4105	3317	3448	5158	5556	4721
Average	2054^{a*}	4229^{b}	4670^{b}		3931^{a}	5618^{b}	6007^{b}	
Grain protein yield, kg ha^{-1}								
Kolorit	131.4	210.7	258.6	200.2^{ns}	264.1	334.1	434.1	344.1^{ns}
Musala	136.7	233.3	286.8	218.9	309.2	395.5	445.5	383.4
Trismart	128.2	191	220.4	179.9	233.6	330.6	344.3	302.8
Average	132.1^{a}	211.7^{b}	255.3^{b}		269.0^{a}	353.4^{ab}	408.0^{b}	

* Values within columns followed by different lowercase letters are significantly different at (P<0.05)

The partial productivity clarifies fertilization's efficiency and is calculated in units of crop yield per unit of nutrient applied. In this study, it was observed that varying levels of fertilization had a significant impact on the partial productivity of nitrogen, phosphorus, and potassium, both individually and in combination. This, in turn, affected the overall productivity of grain and grain protein across three different varieties of triticale. (Table 3). The average partial productivity of nutrients decreases as the level of fertilization increases. This indicates that, for each unit of nutrients applied, less grain or grain protein is produced at higher fertilizer rates compared to lower rates. The result of the double fertilization rates $N_{120}P_{100}K_{40}$ is a lower efficiency of each kilogram of fertilizer element applied. The grain formed per unit of nitrogen is less by 17.7 kg, per unit of phosphorus by 21.1 kg, and per kilogram of fertilizer potassium by 53.0 kg.

The application of nitrogen, phosphorus, and potassium fertilizers significantly impacts the partial productivity of grain protein yield (Table 3). The average partial productivity of nutrients for the grain protein yield of triticale varieties shows a trend similar to that of grain yield. The higher fertilization level lowers by an average of 14.0% the partial productivity of nitrogen, phosphorus, and potassium compared to

$N_{60}P_{50}K_{20}$ fertilization. Twofold higher rates reduced partial productivity for grain protein by 0.5 kg kg^{-1} for PFPpr-N, 0.6 kg kg^{-1} for PFPpr-P and 1.4 kg kg^{-1} for PFPpr-K. At both fertilization levels, the highest mean values for partial potassium productivity were found for grain protein yield of 9.98 ($N_{60}P_{50}K_{20}$) and 8.59 ($N_{120}P_{100}K_{40}$). The productivity of nitrogen and phosphorus to form grain protein yield from triticale is in a relatively narrow range of 2.86 – 3.99 kg kg^{-1}. The average partial productivity of applied PFP-NPK nutrients is higher at the low $N_{60}P_{50}K_{20}$ fertilization level. It is 28.1 kg kg^{-1} for grain yield and 1.54 kg kg^{-1} for grain protein yield. The increase in fertilization for triticale has been shown to reduce the partial productivity of 1 kg of NPK. The results indicate a more significant reduction of 8.2 kg kg^{-1} in partial productivity for grain yield PFPg-NPK, while partial productivity for grain protein PFPpr-NPK is reduced by 0.2 kg kg^{-1}. These results correspond with what was found by Dibb (2000) that for a given soil and growing conditions, the efficiency of nutrient utilization in most cases decreases with increasing amount of element applied.

Table 3. Effect of the fertilization level on the productivity and partial factor productivity of triticale.

Variables	$N_{60}P_{50}K_{20}$	$N_{120}P_{100}K_{40}$	Difference
Grain yield	3651	5185***	1534.0
Protein grain yield	199.7	343.4***	143.7
PFPg-N	60.9	43.2***	-17.7
PFPg-P	73.0	51.9***	-21.1
PFPg-K	182.6	129.6***	-53.0
PFPg-NPK	28.1	19.9***	-8.2
PFPpr-N	3.33	2.86***	-0.5
PFPpr-P	3.99	3.43**	-0.6
PFPpr-K	9.98	8.59**	-1.4
PFPpr-NPK	1.54	1.32**	-0.2

** significance at P<0.05, *** significance at P<0.01, PFPg-partial factor productivity for grain yield, PFPpr-partial factor productivity for protein yield

The varietal response of triticale in productivity of nitrogen, phosphorus, and potassium for grain yield on average over the three years is weak and insignificant (Table 4). However, both fertilization levels tended to make more efficient use of nutrients from soil stocks and applied fertilizers to form yield grain of variety Musala. Lower values of PFPg-N, PFPg-P and of PFPg-K are found for Trismart cultivar, while the standard Kolorit occupies an intermediate position. These data reflect the grain yields obtained from the different varieties. Growing Musala variety at an increased fertilization level $N_{120}P_{100}K_{40}$ reduces the partial productivity of nitrogen, phosphorus, and grain potassium by 20.1 kg kg^{-1}, 24.3 kg $kg^{-1,}$ and 60.5 kg kg^{-1}, respectively, compared to fertilization with $N_{60}P_{50}K_{20}$. The differences in nutrient yield performance between the two fertilization levels by the Trismart variety were 16.0 kg kg^{-1} for PFPg-N, 19.1 kg kg^{-1} for PFPg-P, and 47.8 kg kg^{-1} for PFPg-K. The values of the partial productivity of the nutrients for grain yield from the triticale vary widely: 28.7-88.4 kg kg^{-1} for PFPg-N, 34.5-106.0 kg kg^{-1} for PFPg-P, 86.2-265.1 kg kg^{-1} for PFPg-K. Within the framework of this study, the lowest values for the partial productivity of nitrogen, phosphorus, and potassium were found in the variety Trismart grown at $N_{120}P_{100}K_{40}$ level in the climatically unfavourable 2017. The productivity of all three elements is highest in the variety Musala, fertilized with $N_{60}P_{50}K_{20}$ in 2019.

Table 4. Partial factor productivity of nitrogen, phosphorus, and potassium for grain yield of triticale depending on the fertilization level and cultivar, kg kg^{-1}.

Year	2017	2018	2019	Average	2017	2018	2019	Average
Fertilization	$N_{60}P_{50}K_{20}$				$N_{120}P_{100}K_{40}$			
PFPgrain-N								
Kolorit	33.6	67.1	76.7	59.1 ^{ns}	32.7	45.6	48.7	42.3 ^{ns}
Musala	36.0	80.1	88.4	68.1	36.8	51.9	55.2	48.0
Trismart	33.2	64.3	68.4	55.3	28.7	43.0	46.3	39.3
Average	34.2 ^{a*}	70.5 ^{b}	77.8 ^{b}		32.8 ^{a}	46.8 ^{b}	50.1 ^{b}	
PFPgrain-P								
Kolorit	40.3	80.6	92.1	71.0 ^{ns}	39.3	54.7	58.4	50.8 ^{ns}
Musala	43.2	96.1	106.0	81.8	44.2	62.2	66.2	57.5
Trismart	39.8	77.1	82.1	66.3	34.5	51.6	55.6	47.2
Average	41.1 ^{a}	84.6 ^{b}	93.4 ^{b}		39.3 ^{a}	56.2 ^{b}	60.1 ^{b}	
PFPgrain-K								
Kolorit	100.7	201.4	230.2	177.4 ^{ns}	98.1	136.8	146.1	127.0 ^{ns}
Musala	108.1	240.2	265.1	204.4	110.5	155.6	165.6	143.9
Trismart	99.5	192.8	205.3	165.8	86.2	129.0	138.9	118.0
Average	102.7 ^{a}	211.5 ^{b}	233.5 ^{b}		98.3 ^{a}	140.4 b	150.2 ^{b}	

[*] Values within columns followed by different lowercase letters are significantly different at (P<0.05)

The climatic conditions during the triticale vegetation have a significant effect on the partial productivity of nitrogen, phosphorus, and potassium for grain yield (Table 4). In the climate-friendly 2018 and 2019 years, the partial nitrogen productivity for grain yield is on average 74.2 kg kg^{-1} when fertilized with $N_{60}P_{50}K_{20}$ and an average of 48.5 kg kg^{-1} at the $N_{120}P_{100}K_{40}$ level. In the same years, the partial productivity of phosphorus is in the range of 84.6-93.4 kg kg^{-1} ($N_{60}P_{50}K_{20}$) and 56.2-60.1 kg kg^{-1} ($N_{120}P_{100}K_{40}$). The partial productivity of potassium for grain yield is more than twice as high as that of nitrogen and phosphorus, with favourable hydro-thermal conditions for triticale averaging 119.4 kg kg^{-1} ($N_{60}P_{50}K_{20}$) and 145.3 kg kg^{-1} ($N_{120}P_{100}K_{40}$). Lower average values for the three varieties were obtained in the dry year 2017 compared to those of 2018 and 2019. This is found at both fertilization levels. Unfavourable hydro-thermal conditions in 2017 reduced the partial productivity of nitrogen for grain by 40.0 kg kg^{-1} at the level of $N_{60}P_{50}K_{20}$ and by 15.6 kg kg^{-1} at $N_{120}P_{100}K_{40}$. Drought led to the formation of less grain per unit of phosphorus applied, with a reduction of 47.9 kg kg^{-1} at the $N_{60}P_{50}K_{20}$ level and 18.8 kg kg^{-1} at $N_{120}P_{100}K_{40}$. Decreases of 119.8 kg kg^{-1} ($N_{60}P_{50}K_{20}$) and 47.0 kg kg^{-1} ($N_{120}P_{100}K_{40}$) were found in the partial productivity of grain potassium. The varietal response of triticale is unproven in terms of the partial productivity of nitrogen, phosphorus, and potassium for grain protein yield on average over the three years (Table 5). This is demonstrated at both fertilization levels. According to Alaru et al (2003), the main factor that affects the protein content and the grain yield is the variety, not the nitrogen fertilization. The results obtained were unidirectional, with the observed trend by the three cultivars for partial productivity of the grain yield nutrient. The highest partial productivity for grain protein yield of 4.78 kg kg^{-1} for applied nitrogen, 5.74 kg kg^{-1} for applied phosphorus, and 14.34 kg kg-1 for applied potassium was observed in the variety Musala fertilizer with $N_{60}P_{50}K_{20}$ in 2019. The values of these indicators are lowest in the variety Trismart grown at an increased fertilization level $N_{120}P_{100}K_{40}$ during the climatic unfavourable 2017 and are 1.95 kg kg^{-1} for PFPpr-N, 2.34 kg kg^{-1} for PFPpr-P and 5.84 kg kg^{-1} for PFPpr-K. The less favorable conditions in 2017 led to lower values of the partial productivity of nitrogen, phosphorus, and potassium compared to the other two experimental years. Quantitatively the difference is more significant at the low fertilization level $N_{60}P_{50}K_{20}$. In the same year, the resulting grain protein on average for the varieties was less by 1.33–2.05 kg per kilogram of nitrogen applied, 1.59-2.47 kg per kilogram of phosphorus fertilizer, and 3.97-6.15 kg per kilogram of potassium fertilizer. A proven effect of the year factor on the partial productivity of nitrogen, phosphorus, and potassium for grain protein yield when fertilizing triticale with $N_{120}P_{100}K_{40}$ was found between the average annual values of 2017 and 2019. More favorable hydro-thermal conditions in 2019 led to an average increase of 51% in partial productivity of the elements. Gülmezoğlu and Kutlu (2017) observed that increased N rates stimulate the grain protein and the total N uptake, as the highest protein content was recorded when applying 160 kg ha^{-1}. The same authors reported that the increased N rates decrease all nitrogen use efficiency indexes. Moreover, those indices differed according to the triticale genotype, and the agronomic efficiency was highest at a 40 kg ha^{-1} application rate, when each kg of applied nitrogen produced 8.8 kg kg $^{-1}$ grain. Sobkowicz and Śniady (2004) determined that triticale realized the highest yields at 23 kg per kg N. The agronomic efficiency could be affected by abiotic factors, as well as the genotype, but in general, the parameter decreases while increasing levels of N (Sobkowicz and Śniady, 2004; Aynehband et al., 2012; Janušauskaitė, 2013).

Table 5. Partial factor productivity of nitrogen, phosphorus, and potassium for protein yield of triticale depending on the fertilization level and cultivar, kg kg^{-1}.

Year	2017	2018	2019	Average	2017	2018	2019	Average
Fertilization	$N_{60}P_{50}K_{20}$				$N_{120}P_{100}K_{40}$			
PFPpr-N								
Kolorit	2.19	3.51	4.31	3.34 ^{ns}	2.20	2.78	3.62	2.87 ^{ns}
Musala	2.28	3.89	4.78	3.65	2.58	3.30	3.71	3.20
Trismart	2.14	3.18	3.67	3.00	1.95	2.76	2.87	2.52
Average	2.20 ^{a*}	3.53 ^{b}	4.25 ^{b}		2.24 ^{a}	2.95 ^{ab}	3.40 ^{b}	
PFPpr-P								
Kolorit	2.63	4.21	5.17	4.00 ^{ns}	2.64	3.34	4.34	3.44 ^{ns}
Musala	2.73	4.67	5.74	4.38	3.09	3.96	4.46	3.83
Trismart	2.56	3.82	4.41	3.60	2.34	3.31	3.44	3.03
Average	2.64 ^{a}	4.23 ^{b}	5.11 ^{b}		2.69 ^{a}	3.53 ^{ab}	4.08 ^{b}	
PFPpr-K								
Kolorit	6.57	10.54	12.93	10.01 ^{ns}	6.60	8.35	10.85	8.60 ^{ns}
Musala	6.84	11.67	14.34	10.95	7.73	9.89	11.14	9.59
Trismart	6.41	9.55	11.02	8.99	5.84	8.27	8.61	7.57
Average	6.61 ^{a}	10.58 ^{b}	12.76 ^{b}		6.72 ^{a}	8.84 ^{ab}	10.20 ^{b}	

* Values within columns followed by different lowercase letters are significantly different at (P<0.05)

A strong correlation has been observed between the grain yield and the grain protein yield (0.936) and between their partial factors' productivity (0.941) (Table 6). The relationship between the yield and the partial factors productivity of the protein is moderately dependent (0.584). The scatterplots illustrate the determined relations (Figure 2) and define the strong positive relation between the yield and the protein as roughly linear. Wojtkowiak et al. (2015) also reported a linear dependence between the protein content and the grain yield. In their findings, the protein yield increased with an increase in the grain yields, as the coefficient of determination was close to the linear correlation coefficient.

Table 6. Correlation matrix (Pearson).

Variables	Yield	Protein	PFP-Y	PFP-P
Yield	1			
Protein	0.936	1		
PFP-Y	0.397	0.098	1	
PFP-P	0.584	0.361	0.941	1

*Values in bold are different from 0 with a significance level alpha=0,05

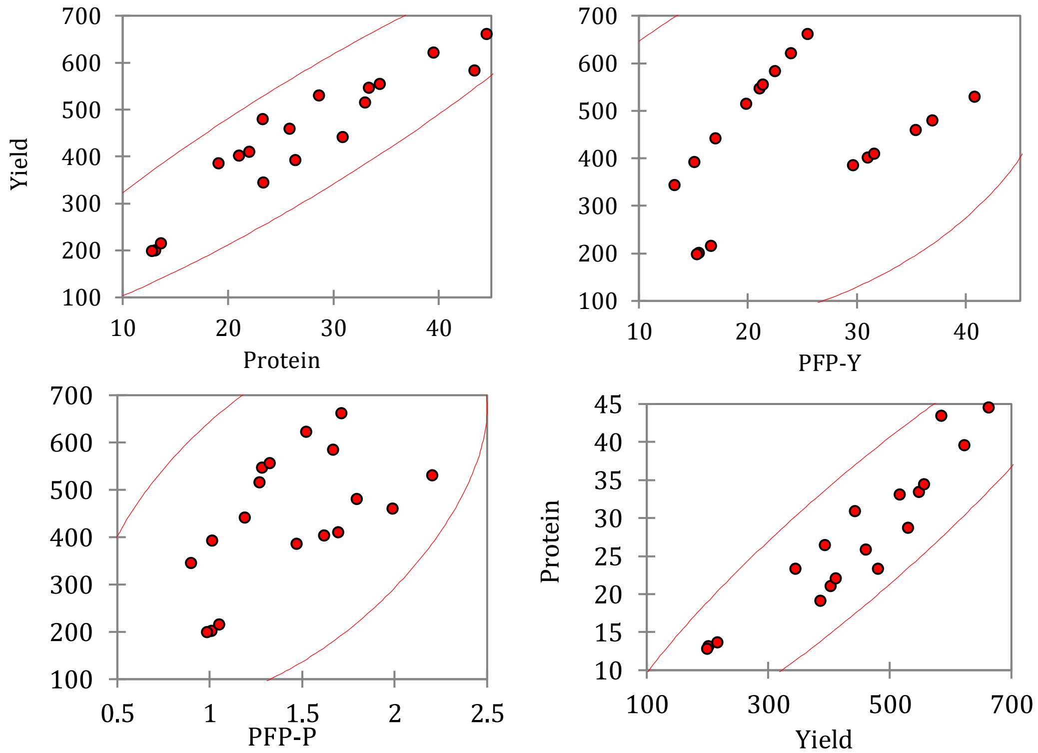

Figure 2. Correlation scatter plots between Yield, protein and PFP.

Conclusion

Higher levels of fertilization significantly increased not only the overall yield but also the yield of crude protein in the three varieties of triticale. Throughout the testing period, productivity varied greatly due to mineral nutrition and yearly conditions, while the differences among the varieties were not significant. Fertilization level had a significant impact on the partial productivity of nitrogen, phosphorus, and potassium. The average partial productivity of nutrients decreases as the level of fertilization increases. For each unit of nutrients applied, less grain or grain protein is produced at higher fertilizer rates compared to lower rates. The result of the double fertilization rates $N_{120}P_{100}K_{40}$ is a lower efficiency of each kilogram of fertilizer element applied. The varietal response of triticale in the productivity of nitrogen, phosphorus, and potassium for grain yield is weak and insignificant. However, both fertilization levels tended to make more efficient use of nutrients from soil stocks and applied fertilizers to form the grain yield of the variety Musala.

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Natural zeolite enhances tomato yield, reduces nitrate accumulation, and immobilizes heavy metals in fertilized dark chestnut soil

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Abstract

Tomato (Solanum lycopersicum L.) is a widely cultivated vegetable crop in Kazakhstan, yet its productivity and quality are often limited by soil degradation, nutrient imbalances, and the excessive use of mineral fertilizers. Natural zeolites, particularly clinoptilolite, offer potential as soil amendments due to their high cation exchange capacity, water retention properties, and ability to regulate nutrient availability. This study aimed to evaluate the effects of natural zeolite (2 t/ha), alone and in combination with two mineral fertilizer doses ($N_{45}P_{45}K_{45}$ and $N_{90}P_{90}K_{90}$), on tomato yield, fruit quality, soil heavy metal content, and economic profitability under dark chestnut soil conditions in southeastern Kazakhstan. A field experiment was conducted using a randomized complete block design with six treatments and three replications. Results showed that all treatments increased yield compared to the control (21.7 t/ha), with the highest yield (29.1 t/ha) observed under the zeolite + $N_{90}P_{90}K_{90}$ treatment. Fruit quality improved in terms of dry matter (up to 5.46%) and sugar content (up to 3.80%) with zeolite and fertilizer combinations. Nitrate accumulation in fruits was highest under $N_{90}P_{90}K_{90}$ alone (78 mg/kg) but decreased significantly when combined with zeolite (64 mg/kg), indicating the mineral's capacity to reduce nitrate uptake. Heavy metal analysis revealed that zeolite reduced the bioavailability of cadmium and lead in soil, keeping concentrations below permissible limits. Economic evaluation indicated that the zeolite-only treatment provided the highest profitability (171%) due to relatively low input costs and moderate yield gains. Overall, the results demonstrate that zeolite, especially when integrated with moderate fertilizer inputs, enhances tomato productivity, improves fruit safety, and supports sustainable soil management. Its use can be particularly beneficial in resource-limited and environmentally sensitive agricultural systems.

Keywords: Tomato, zeolite, clinoptilolite, mineral fertilizers, nitrate, heavy metals, yield, sustainable agriculture.

Introduction

Tomato (Solanum lycopersicum L.) is one of the most widely cultivated vegetable crops globally, valued for its nutritional content, economic significance, and versatility in both fresh consumption and food processing (Grandillo et al., 1999; Maxatova et al., 2021; Bihon et al., 2022; Tastanbekova et al., 2024). In Kazakhstan, tomato production has steadily increased in recent years, especially in irrigated regions with favorable thermal regimes and market access (Shmelev et al., 2021; HelgiLibrary, 2024). However, achieving high and sustainable tomato yields remains a challenge due to declining soil fertility, inefficient nutrient use, and

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environmental concerns associated with excessive fertilizer application (Ay et al., 2022; Ahmed et al., 2022; Maffia et al., 2023).

Conventional agricultural practices often rely heavily on mineral fertilizers to increase crop productivity (Omer et al., 2024). While effective in the short term, the continuous use of high doses of nitrogen, phosphorus, and potassium fertilizers can lead to nutrient imbalances, nitrate accumulation in edible plant parts, soil acidification, and environmental contamination (Anas et al., 2020). Moreover, the economic burden of fertilizer inputs on smallholder farmers necessitates more efficient and cost-effective nutrient management strategies (Mohammed et al., 2024).

In recent years, natural zeolites—particularly clinoptilolite—have gained attention as multifunctional soil amendments in sustainable agriculture (Mondal et al., 2021; Cataldo et al., 2021). Zeolites are hydrated aluminosilicates with a high cation exchange capacity, capable of adsorbing and slowly releasing essential nutrients such as ammonium and potassium (Cataldo et al., 2021; Khamkure et al., 2025). In addition, zeolites improve soil structure, increase water retention, buffer soil pH, and reduce leaching losses, which can ultimately enhance crop performance under varying environmental conditions (Nakhli et al., 2017. Mondal et al., 2021; Javaid et al., 2024). Kazakhstan is endowed with extensive natural reserves of clinoptilolite, a prominent member of the zeolite group, characterized by its high cation exchange capacity, thermal stability, and molecular sieving properties. Among the most significant deposits are those located in Karatau, Kounrad, Kokshetau, Terekty, and Shankanai, which are recognized for both their volume and mineralogical quality. These natural clinoptilolite reserves have found widespread applications across various sectors, including crop production, animal nutrition, water treatment, and the remediation of contaminated soils. Owing to its physicochemical properties, Kazakhstani clinoptilolite serves as an effective soil conditioner, improving nutrient retention and reducing leaching losses. Importantly, these deposits have historically been employed in agricultural contexts without prior enrichment or combination with synthetic fertilizers (Sadenova et al., 2016; Sultanbayeva et al., 2022; Vassilina et al., 2023), underscoring their intrinsic agronomic potential.

Several studies have demonstrated that integrating zeolite with mineral fertilizers can lead to higher yields, improved fruit quality, and reduced nitrate accumulation in crops (Wea et al., 2018; Vassilina et al., 2023, 2024; Javaid et al., 2024). However, limited information is available on the effects of zeolite and its interaction with fertilizer regimes on tomato production, particularly in the context of dark chestnut soils common to southeastern Kazakhstan. Dark chestnut soil represents one of the major soil types in Kazakhstan, occupying a substantial portion of the nation's arable land (Saparov, 2014). As a fertile soil resource, it plays a vital role in sustaining agricultural productivity, ensuring food security, supporting the national economy, and maintaining biodiversity across Kazakhstan. Therefore, the objective of this study was to evaluate the impact of natural zeolite (clinoptilolite) and its combination with different doses of mineral fertilizers on tomato yield, fruit quality, heavy metal accumulation in soil, and economic performance under open-field conditions.

Material and Methods

Study Area

The study was conducted during the 2023 growing season at the educational and experimental field station of the Kazakh Research Institute of Potato and Vegetable Growing, located in southeastern Kazakhstan. The site is characterized by dark chestnut soils, which are widely distributed across the foothill regions and are known for their medium fertility and sensitivity to irrigation-induced degradation.

The region experiences a sharply continental climate, with an average temperature of 24–26°C in July and -8 to -12°C in January. The annual precipitation ranges from 350 to 600 mm, of which 120–300 mm falls during the growing season. The total sum of active temperatures is approximately 3,100–3,400°C, providing a favorable thermal regime for vegetable production under irrigation.

Soil Characteristics

The experimental soil is classified as dark chestnut, with a loamy texture and weak structural development. The topsoil (0–20 cm) has a humus content of 2.27%, available nitrogen of 61.6 mg/kg, phosphorus 38 mg/kg, and potassium 240 mg/kg. The soil exhibits a slightly alkaline reaction (pH 8.36–8.37) and a $CaCO_3$ content of 1.23% in the topsoil, decreasing to 1.14% at 20–40 cm. The bulk density ranges from 1.1 to 1.2 g/cm^3, and minimum field moisture capacity is 26.6%. Due to weak aggregate structure, the soil is prone to surface crusting and compaction under irrigation or rainfall events. The mechanical composition of the 0–20 cm layer is dominated by the 0.05–0.01 mm fraction (41.41%) and fine silt (<0.001 mm, 18.68%), while the subsoil (20–40 cm) contains a higher proportion of coarser particles.

Experimental Design and Treatments

A randomized complete block design (RCBD) with three replications was used. The total plot size for each treatment was 63 m^2 (4.2 × 15 m). The experiment included six treatment combinations:

- Control (no fertilizer)
- Zeolite (2 t/ha)
- $N_{45}P_{45}K_{45}$
- $N_{90}P_{90}K_{90}$
- Zeolite (2 t/ha) + $N_{45}P_{45}K_{45}$
- Zeolite (2 t/ha) + $N_{90}P_{90}K_{90}$

Fine-fraction zeolite used in the experiment was sourced from the Shankhanai deposit and consisted primarily of clinoptilolite (75–77%). Its chemical composition included 68.6% SiO_2, 18.5% Al_2O_3, 8.6% CaO, 2.2% MgO, 1.82% K_2O, and 1.5% Na_2O. The cation exchange capacity was 112 mmol/kg, and BET surface area was 32 m^2/g. The bulk density was 2.14 g/cm^3, and pH was 8.3.

Fertilizers applied included ammonium nitrate (34% N), ammophos (12% N, 52% P_2O_5), and potassium sulfate (50% K_2O). Fertilizer applications were made prior to transplanting, according to treatment specifications.

The tomato variety used was *Samaladay*, adapted to the local agro-climatic conditions. Transplanting was delayed until May 27, 2023, due to low temperatures. Seedlings, aged 50 days, were transplanted under open field conditions using a 70 × 30 cm spacing. Irrigation was performed via furrows between the rows, with frequency adjusted to growth stages: every 2–3 days after transplanting and weekly during fruit development. Pest control was implemented using Coragen (chlorantraniliprole 200 g/L) at 0.15 L/ha.

Fruits were harvested manually once per week upon reaching technical maturity. Harvested produce from each plot was weighed immediately to determine fresh yield.

Laboratory Analysis

Fruit Quality parameters: Dry matter content was measured gravimetrically (GOST 28561-90), total sugars by Bertrand's method (GOST 13192-73), and nitrate concentration potentiometrically with diphenylamine (GOST 29270-95).

Heavy Metals concentration: DTPA-extractable forms of Zn, Cu, Cd, and Pb were determined using atomic absorption spectrometry (GOST 30178-96).

Economic Analysis

The economic assessment included input costs (seeds, fertilizers, pesticides, irrigation, labor), calculated based on actual usage and 2023–2024 market prices. Revenue was estimated from yield and average market price (70,000 tenge/ton ≈ 135.66 USD/ton). Net income and profitability were computed using:

$$\text{Profitability (\%)} = (\text{Net Income} / \text{Costs}) \times 100$$

Statistical Analysis

Data were statistically evaluated using one-way ANOVA. Treatment means were compared using Fisher's LSD test and Tukey's HSD at a significance level of $p < 0.05$. All statistical computations were performed using SigmaPlot 11.0 and Microsoft Excel 2010.

Results and Discussion

Tomato Yield Performance

Tomato yield was significantly influenced by the application of zeolite and mineral fertilizers. As shown in Table 1, the control treatment (no fertilizer) produced the lowest yield (21.7 t/ha). The application of 2 t/ha zeolite alone increased yield to 24.8 t/ha, reflecting a gain of 3.1 t/ha. This improvement is likely due to enhanced soil structure and water retention facilitated by zeolite.

Table 1. Effect of zeolite and fertilizers on tomato yield

Treatment	Yield (t/ha)	Yield increase (t/ha)
Control (no fertilizer)	21.7 ± 0.65	–
Zeolite (2 t/ha)	24.8 ± 0.70	3.1
$N_{45}P_{45}K_{45}$	23.7 ± 0.68	2.0
$N_{90}P_{90}K_{90}$	26.4 ± 0.70	4.7
Zeolite (2 t/ha) + $N_{45}P_{45}K_{45}$	27.9 ± 0.80	6.2
Zeolite (2 t/ha) + $N_{90}P_{90}K_{90}$	29.1 ± 0.85	7.4
$LSD_{0.5}$	–	2.12

Fertilizer-only treatments also improved yield: $N_{45}P_{45}K_{45}$ resulted in a 2.0 t/ha increase, and $N_{90}P_{90}K_{90}$ in a 4.7 t/ha increase. However, the highest yield was achieved with the combination of zeolite and $N_{90}P_{90}K_{90}$ (29.1 t/ha), which was 7.4 t/ha above the control. The statistical analysis confirmed significance ($LSD_{0.5}$ = 2.12 t/ha). This indicates a synergistic effect, likely due to reduced nutrient leaching and improved nutrient availability, aligning with the findings of Ippolito et al. (2011) and Malekian et al. (2011). These results are also consistent with Kavvadias et al. (2023), who observed that clinoptilolite zeolite improved fresh weight yield of lettuce, particularly in moderately acidic soils, through enhanced nutrient retention and water management. Their findings further support that zeolite's performance is closely tied to soil type and fertilization strategy, confirming its synergistic role in nutrient use efficiency and yield optimization. These results are also supported by Rahmani et al. (2023), who reported that the combined use of vermicompost and clinoptilolite zeolite significantly improved the yield and nutrient uptake of Nigella sativa L. under semi-arid conditions. Their study demonstrated a strong interaction effect between zeolite and organic input rates, resulting in enhanced biomass and yield components. Similar to our findings, the authors attributed the improved productivity to increased nutrient availability, water retention, and soil microbial activity. These synergies underline the agronomic potential of zeolite as a sustainable amendment, particularly when integrated with conventional fertilization strategies. These findings are consistent with broader observations reported by Jarosz et al. (2022), who reviewed over 100 studies on zeolite-based fertilization strategies. Their synthesis highlighted that clinoptilolite zeolite enhances crop yields primarily through improved nitrogen retention, reduction of nutrient leaching, and better soil moisture availability. Notably, yield increases were most pronounced when zeolite was combined with NPK fertilizers, particularly under conditions of moderate soil fertility and irrigation limitations

Fruit Quality Parameters

The application of fertilizers and zeolite also influenced the biochemical composition of tomato fruits (Table 2). Dry matter content ranged from 5.04% to 5.46%. The lowest value was seen in the zeolite-only treatment, while the highest (5.46%) was observed in the zeolite + $N_{90}P_{90}K_{90}$ variant. These results suggest that adequate mineral nutrition enhances photosynthate accumulation, especially when zeolite is included to regulate nutrient release. Total sugar content followed a similar trend, increasing from 3.55% in the control to 3.80% in the zeolite + $N_{90}P_{90}K_{90}$ treatment. Notably, even the zeolite-alone and zeolite + $N_{45}P_{45}K_{45}$ treatments showed higher sugar levels than the control, suggesting that zeolite contributes to improved fruit taste by supporting balanced nutrient uptake.

Table 2. Effect of treatments on dry matter, sugar, and nitrate content in tomato fruits

Treatment	Dry matter (%)	Total sugar (%)	Nitrate (mg/kg)
Control	5.07 ± 0.076	3.55 ± 0.015	68 ± 6.51
Zeolite (2 t/ha)	5.04 ± 0.100	3.58 ± 0.005	61 ± 6.56
$N_{45}P_{45}K_{45}$	5.10 ± 0.076	3.60 ± 0.015	73 ± 5.13
$N_{90}P_{90}K_{90}$	5.36 ± 0.076	3.60 ± 0.015	78 ± 5.51
Zeolite (2 t/ha) + $N_{45}P_{45}K_{45}$	5.12 ± 0.064	3.75 ± 0.005	59 ± 5.51
Zeolite (2 t/ha) + $N_{90}P_{90}K_{90}$	5.46 ± 0.076	3.80 ± 0.010	64 ± 5.51

Nitrate levels were elevated in all fertilizer-only treatments, peaking at 78 mg/kg in the $N_{90}P_{90}K_{90}$ treatment. However, zeolite application mitigated this accumulation. The lowest nitrate value (59 mg/kg) was recorded in the zeolite + $N_{45}P_{45}K_{45}$ variant, indicating zeolite's role in reducing nitrate leaching and root zone accumulation. These results are in agreement with Cataldo et al. (2021) and Jarosz et al. (2022). The observed improvements in fruit firmness and total soluble solids (TSS) under zeolite treatments may be attributed to better nutrient retention and water availability during the fruit maturation stage. Similar findings were reported by Milošević and Milošević (2017), who investigated the effects of natural zeolite, farmyard manure, and mineral fertilizers on apple cultivars. Although their study revealed no statistically significant differences in fruit quality traits among treatments, they noted that fresh weight and sugar content tended to improve under zeolite-inclusive fertilization, particularly in soils with moderate fertility. These results highlight the context-dependent nature of zeolite's effect on fruit quality and underscore the importance of soil conditions and cultivar response in determining outcome. The improvements in fruit weight and sweetness observed under zeolite application are consistent with other studies. For instance, Choo et al. (2020) reported that the co-application of clinoptilolite zeolite with NPK fertilizers significantly improved fruit weight, length, diameter, and TSS (◦ Brix) in Carica papaya cultivated on tropical peat soils. The study attributed these improvements to zeolite's high cation exchange capacity and pH-buffering ability, which enhanced the availability and uptake of key nutrients (NH_4^+, NO_3^-, P, K) during critical growth stages. These findings support our results, indicating that zeolite's role in nutrient regulation contributes meaningfully to fruit quality enhancement under challenging soil conditions. Fruit quality improvements observed in this study align with the findings summarized by Jarosz et al. (2022), who reported that zeolite application can positively affect biochemical traits such as sugar content, firmness, and nitrate accumulation in various fruits and vegetables. The slow-release behavior and buffering capacity of zeolite were identified as key mechanisms that support more stable nutrient supply during fruit development

Heavy Metal Mobility in Soil

The accumulation of mobile heavy metals in the 0–20 cm soil layer was affected by fertilizer and zeolite applications (Table 3). The analysis of mobile heavy metals in the 0–20 cm soil layer showed that fertilizer treatments increased cadmium (Cd) and lead (Pb) levels beyond the control. Particularly, the $N_{45}P_{45}K_{45}$ treatment resulted in 0.90 mg/kg Cd and 0.60 mg/kg Pb, exceeding recommended limits for long-term soil health.

Table 3. Heavy metal content in the 0–20 cm soil layer

Treatment	Zn (mg/kg)	Cu (mg/kg)	Cd (mg/kg)	Pb (mg/kg)
Control	1.20 ± 0.045	0.30 ± 0.030	0.40 ± 0.025	0.20 ± 0.035
Zeolite (2 t/ha)	1.60 ± 0.050	0.20 ± 0.025	0.40 ± 0.020	0.00 ± 0.010
$N_{45}P_{45}K_{45}$	1.50 ± 0.040	0.30 ± 0.020	0.90 ± 0.030	0.60 ± 0.045
$N_{90}P_{90}K_{90}$	1.60 ± 0.035	0.70 ± 0.050	0.70 ± 0.025	0.30 ± 0.030
Zeolite (2 t/ha) + $N_{45}P_{45}K_{45}$	1.40 ± 0.030	0.30 ± 0.025	0.30 ± 0.020	0.10 ± 0.020
Zeolite (2 t/ha) + $N_{90}P_{90}K_{90}$	1.40 ± 0.025	0.30 ± 0.030	0.20 ± 0.015	0.20 ± 0.025
MPC	23	3.0	0.5	32.0

In contrast, the application of zeolite alone or in combination with fertilizers significantly reduced these levels. Zeolite + $N_{90}P_{90}K_{90}$ reduced Cd to 0.20 mg/kg and Pb to 0.20 mg/kg. These reductions confirm zeolite's ion-exchange capacity and metal sorption potential as demonstrated by Filcheva and Tsadilas (2002). Copper (Cu) and zinc (Zn) contents were less variable but also decreased with zeolite addition. The use of zeolite significantly reduced the accumulation of heavy metals such as Cd in tomato fruits in our study, which can be attributed to the reduced mobility and enhanced fixation of metals in the soil matrix. These results are supported by Bertalan-Balázs et al. (2024), who demonstrated that the application of natural zeolite and biochar in Cd-contaminated calcareous soils led to a marked decrease in the DTPA- and EDTA-extractable Cd concentrations. Their findings showed that zeolite increased the fraction of Cd bound to carbonate and iron–manganese oxides, effectively reducing its bioavailability. Moreover, zeolite improved soil cation exchange capacity and pH, further stabilizing Cd and limiting its uptake by plants. These observations confirm the role of zeolite as a promising soil amendment for mitigating heavy metal risks in agricultural production systems. Our findings that zeolite addition significantly reduced Cd and Pb accumulation in tomato fruits are in agreement with Damian et al. (2013), who demonstrated that both natural and organo-zeolitic amendments led to substantial reductions in Pb and Cd bioavailability in contaminated Romanian soils. Their long-term greenhouse study showed that zeolite increased soil pH, cation exchange capacity, and organic matter content, resulting in reduced mobility and uptake of Pb and Cd. Moreover, their EDX and XRD analyses confirmed the structural incorporation of these heavy metals into the zeolite matrix, further highlighting the strong affinity of clinoptilolite-rich zeolite for Pb^{2+} and Cd^{2+} ions. These findings support our results and underline zeolite's role as an effective amendment for minimizing food chain contamination from heavy metals. Zeolite's capacity to reduce bioavailable forms of Cd and Pb, as demonstrated in this experiment, has been thoroughly reviewed by Jarosz et al. (2022). Their analysis confirmed that natural zeolites exhibit high sorption affinity for divalent heavy metal ions such as Cd^{2+}, Pb^{2+}, and Zn^{2+}, leading to immobilization through ion exchange, surface complexation, and micropore trapping. These mechanisms not only reduce metal uptake by plants but also contribute to long-term stabilization in the soil matrix.

Economic Efficiency of Treatments

The economic analysis revealed that the zeolite-only treatment was the most profitable (171%) due to its low cost and moderate yield increase (Table 4). The economic analysis revealed that while the highest yield was achieved with zeolite + $N_{90}P_{90}K_{90}$ (29.0 t/ha), this treatment had a relatively low profitability (73%) due to its high cost (2,281.74 USD/ha). In contrast, the zeolite-only treatment yielded a lower production (25.4 t/ha) but resulted in the highest profitability (171%) due to its lower cost and reasonable return. This finding underscores the potential of zeolite as a cost-effective alternative in low-input systems, particularly in regions where fertilizer costs limit profitability. The $N_{45}P_{45}K_{45}$ treatment also demonstrated good profitability (103%), indicating that moderate fertilization may be economically more favorable when combined with zeolite. This supports the application of integrated nutrient management strategies for both environmental sustainability and economic viability.

Table 4. Economic efficiency of tomato production under different treatments

Treatment	Yield (t/ha)	Revenue (USD/ha)	Cost (USD/ha)	Net Income (USD/ha)	Profitability (%)
Control	22.3	2,945.82	–	–	–
Zeolite (2 t/ha)	25.4	3,364.37	1,240.44	2,123.93	171
$N_{45}P_{45}K_{45}$	24.3	3,216.14	1,582.29	1,633.85	103
$N_{90}P_{90}K_{90}$	27.0	3,582.42	2,014.50	1,567.92	78
Zeolite (2 t/ha) + $N_{45}P_{45}K_{45}$	28.0	3,786.91	2,203.06	1,583.85	72
Zeolite (2 t/ha) + $N_{90}P_{90}K_{90}$	29.0	3,949.71	2,281.74	1,667.97	73

Conclusion

This study clearly demonstrated that the application of zeolite, either alone or in combination with mineral fertilizers, positively affected tomato yield, fruit quality, heavy metal accumulation in soil, and economic profitability under dark chestnut soil conditions in southeastern Kazakhstan. The highest yield (29.1 t/ha) was obtained with the combined application of 2 t/ha zeolite and a full dose of mineral fertilizers ($N_{90}P_{90}K_{90}$), confirming the synergistic effect of zeolite and nutrients in promoting plant productivity. However, the zeolite-only treatment (2 t/ha) proved to be the most cost-effective, achieving the highest profitability (171%) with acceptable yield improvement, highlighting its potential in low-input production systems.

Zeolite addition also improved tomato fruit quality by enhancing dry matter and sugar contents while reducing nitrate accumulation. The lowest nitrate content (59 mg/kg) was recorded in the zeolite + $N_{45}P_{45}K_{45}$ treatment, suggesting that zeolite can mitigate nitrate build-up even under moderate fertilization regimes. Furthermore, the application of zeolite significantly reduced the bioavailability of cadmium and lead in the topsoil. Particularly, the zeolite + $N_{90}P_{90}K_{90}$ treatment lowered cadmium content to 0.20 mg/kg—well below the maximum permissible concentration—demonstrating the material's environmental safety function. In light of our results and the growing body of evidence, including the extensive review by Jarosz et al. (2022), zeolite application represents a viable pathway toward climate-smart and environmentally responsible agriculture. Its role in reducing nutrient losses, mitigating heavy metal risks, and supporting sustainable fertilizer practices aligns with the objectives of the European Green Deal and global soil health initiatives

In summary, natural zeolite from the Shankhanai deposit represents an effective soil amendment that enhances yield and quality of tomato while improving soil health and economic return. These findings support the integration of zeolite into sustainable fertilization strategies, especially in regions with alkaline, structure-sensitive soils. Further long-term field studies are recommended to evaluate cumulative effects on soil properties and crop rotation systems and assess zeolite's contribution to nutrient cycling, residual effects, and soil microbial balance over multiple growing seasons.

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Effects of vermicompost application rates and irrigation regimes on tomato yield, nutrient uptake and soil properties under greenhouse conditions

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Abstract

Tomato (Solanum lycopersicum L.) is a widely cultivated horticultural crop that responds sensitively to both nutrient availability and water management. The use of vermicompost as an organic fertilizer offers potential to improve plant productivity and soil health, especially under conditions of limited irrigation. This greenhouse study aimed to investigate the effects of different vermicompost application rates and irrigation levels on tomato yield, leaf nutrient uptake, and post-harvest soil properties. The experiment was conducted using a clay soil with low fertility characteristics (organic matter 1.15%, total N 0.06%, available P 5.26 mg/kg) and vermicompost rich in nutrients (total N 1.52%, total P 0.46%, total K 2.85%). Treatments consisted of four vermicompost rates (0, 0.25, 0.5, and 1.0 t/da) combined with three irrigation levels (100%, 75%, and 50% of field capacity) in a completely randomized design with three replications. Tomato plants were grown under controlled greenhouse conditions, and yield per plant, leaf nutrient contents (N, P, K, Ca, Mg), post-harvest soil nutrient status, and biological properties (microbial biomass carbon, soil respiration, enzyme activities) were evaluated. Results indicated that both vermicompost and irrigation level significantly affected tomato yield, which increased from 4.90 kg/plant (control, 50% FC) to 8.00 kg/plant (1.0 t/da, 100% FC). Leaf nutrient concentrations and soil available N, P, K, Ca, and Mg were significantly improved with higher vermicompost doses. Soil microbial biomass and enzymatic activities also responded positively to vermicompost, while water stress had suppressive effects. The interaction between vermicompost and irrigation was generally not significant, suggesting additive but independent effects. In conclusion, the application of vermicompost at 1.0 t/da improved tomato yield, nutrient uptake, and soil quality indicators, even under moderate water stress. This study supports the integration of organic amendments and optimized irrigation as a sustainable strategy for tomato production in protected cultivation systems.

Keywords: Vermicompost, irrigation levels, tomato yield, soil fertility, greenhouse cultivation.

Introduction

Tomato (Solanum lycopersicum L.) is one of the most economically valuable vegetable crops cultivated globally in both open field and protected environments (Padmanabhan et al., 2016). The growing demand

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for high-yielding and high-quality tomato fruits has intensified the use of chemical fertilizers and irrigation practices (Montgomery and Biklé, 2021). However, excessive reliance on inorganic inputs under greenhouse conditions has raised concerns about soil degradation, nutrient imbalance, and reduced fruit quality (Tahat et al., 2020).

In recent years, the application of organic amendments, particularly vermicompost, has gained attention as a sustainable strategy to improve soil fertility and plant productivity (Toor et al., 2024). Kızılkaya et al. (2012) demonstrated that the application of vermicomposted organic wastes significantly enhanced wheat grain and straw yield, as well as the concentrations of nitrogen, phosphorus, and potassium in both soil and plant tissues, compared to untreated and non-vermicomposted treatments. Vermicompost is the stabilized product of organic matter decomposition through the joint activity of earthworms and microorganisms. It is known to contain readily available nutrients (e.g., NO_3^-, PO_4^{3-}, K^+, Ca^{2+}, Mg^{2+}), plant growth-promoting substances, and a rich population of beneficial microbes (Yang et al., 2015). Vermicompost application enhances nutrient uptake, stimulates enzymatic activity, and improves soil structure and microbial biomass, all of which contribute to improved plant growth and fruit yield (Hyder et al., 2015; Demir, Z., 2021; Trang and Chuong, 2025). Arancon et al. (2006), soils amended with vermicompost exhibited higher levels of NH_4-N, NO_3-N, and orthophosphates, as well as increased dehydrogenase activity at harvest, compared to untreated soils.

Tomato is particularly sensitive to both nutrient status and water availability. While adequate irrigation is essential for high productivity, water stress—either deficit or excess—can significantly alter fruit set, yield components, and nutrient transport (Putti et al., 2023; Islamzade et al., 2024). Studies have demonstrated that irrigation levels interact with soil fertility management to influence crop response, with moderate water regimes often optimizing nutrient use efficiency and fruit quality (Kim et al., 2022). According to Yang et al. (2015), tomato plants grown under 60–70% of field capacity with vermicompost treatment exhibited the highest yield and vitamin C content, along with improved soil enzyme activities and nutrient availability, highlighting the critical role of irrigation-fertilizer synergy in greenhouse conditions. However, the interaction between vermicompost and irrigation regimes on tomato performance under greenhouse conditions remains relatively underexplored.

Given the need to improve yield and nutrient quality of tomato in an environmentally friendly manner, integrating organic fertilization strategies with efficient water management could be a key approach. In this paper, vermicompost not only supplies essential nutrients but may also buffer against the negative impacts of water stress by improving soil water-holding capacity and microbial resilience.

The objective of this study was to evaluate the effects of different vermicompost application rates and irrigation levels on tomato yield, leaf nutrient concentrations, and post-harvest soil properties under greenhouse conditions. It was hypothesized that increasing vermicompost rates would improve plant and soil performance, and that moderate irrigation would synergize with organic amendment to optimize tomato yield and nutrient use efficiency.

Material and Methods

Soil, Vermicompost, and Tomato Plant

The experiment was conducted using soil, vermicompost, and tomato plants (F1 tomato). The soil samples were processed and analyzed to determine their physical and chemical properties. The compost used was analyzed for its organic matter content and nutrient composition. The tomato plants were cultivated under controlled greenhouse conditions.

The soil used in the experiment was characterized by several analyses. The texture was determined using the hydrometer method (Bouyoucos, 1962). The pH and electrical conductivity (EC) were measured in a 1:1 soil-water suspension using a pH meter (Peech, 1965) and an EC meter (Bower and Wilcox, 1965), respectively. Calcium carbonate ($CaCO_3$) content was determined volumetrically using the Scheibler calsimeter (Rowell, 2010). Organic matter content was analyzed by the wet oxidation with $K_2Cr_2O_7$ (Walkley and Black, 1934). Total nitrogen (N) content was determined using the Kjeldahl method (Bremner, 1965). Available phosphorus (P) was measured in a 0.5M $NaHCO_3$ extract using a spectrophotometer (Olsen and Dean, 1965). Exchangeable cations (K, Ca and Mg) were extracted with 1 N ammonium acetate; K and Na were determined by flame photometry, while Ca and Mg were measured by EDTA titration (Pratt, 1965; Heald, 1965).

The vermicompost, produced from plant waste and cow dung using Eisenia fetida, was analyzed for its organic matter and nutrient content. Organic matter was assessed by loss on ignition at 550°C. Total nitrogen (N) was determined using the Kjeldahl method. For total phosphorus (P), potassium (K), calcium

(Ca), and magnesium (Mg), samples were subjected to dry ashing. Phosphorus was measured spectrophotometrically, potassium by flame photometry, and calcium and magnesium by atomic absorption spectrophotometry (Jones, 2001).

Greenhouse Conditions and Experimental Setup

The experiment was conducted under controlled greenhouse conditions. The study aimed to investigate the combined effects of different vermicompost doses and irrigation levels on the yield and yield components of tomato (*Solanum lycopersicum* L.). A randomized complete block design was employed with four replications. The main plots consisted of three irrigation levels based on field capacity (FC):

- I1: 100% FC (No stress)
- I2: 75% FC (Moderate water stress)
- I3: 50% FC (Severe water stress)

The sub-plots consisted of four vermicompost doses:

- V0: Control (0 t/da)
- V1: 0.25 t/da
- V2: 0.5 t/da
- V3: 1.0 t/da

Each treatment was applied to polyethylene pots (30 cm diameter × 28 cm height), each filled with 5 kg of air-dried, sieved (4 mm) soil. The fertilizers used were ammonium sulfate (21% N) as the nitrogen source, monoammonium phosphate (12% N, 61% P_2O_5) as the phosphorus source, and potassium sulfate (50% K_2O) as the potassium source. The standard soil fertilization application included 30 kg N/da, 8 kg P_2O_5/da, and 40 kg K_2O/da. Tomato (*F1 hybrid*) seedlings were transplanted on March 10, 2023. One seedling was planted per pot. Vermicompost was thoroughly mixed into the soil prior to transplanting. Irrigation was carried out daily based on pot weight to maintain soil moisture at the assigned levels of field capacity (100%, 75%, or 50%).

Harvest and Measurements

Ripe tomatoes were harvested periodically and total yield per plant (g) was recorded. At the end of the experiment (October 25, 2023), soil and plant samples were collected. Leaf samples from each pot were analyzed for N, P, Ki Ca, and Mg contents (Jones, 2001). Soil samples were analyzed for available nitrogen (NH_4+NO_3) using 1 N KCl extraction followed by Kjeldahl distillation (Bremner, 1965), available phosphorus in a 0.5 M NaHCO3 extract using a spectrophotometer (Olsen and Dean, 1965), and, exchangeable cations (K, Ca and Mg) were extracted with 1 N ammonium acetate; K and Na were determined by flame photometry, while Ca and Mg were measured by EDTA titration (Pratt, 1965; Heald, 1965). Biological properties of the soil, including microbial biomass carbon, basal soil respiration, and enzyme activities, were also measured. Microbial biomass carbon (MBC) was determined using the method of Anderson and Domsch (1978), basal soil respiration (BSR) was measured as described by Anderson (1982), dehydrogenase activity (DHA) was determined following Pepper (1995), catalase activity (CA) was measured by the Beck method (Beck, 1971), and urease activity was measured by the method of Hoffmann und Teicher (1961).

Statistical Analysis

Data were analyzed using ANOVA (SPSS 20.0). Treatment means were compared using the LSD test at $p < 0.05$. Interactions between irrigation level and vermicompost dose were also evaluated.

Results and Discussion

Before initiating the experiment, the basic physico-chemical characteristics of the soil were determined to assess its fertility status. The results of these analyses are shown in Table 1.

Table 1. Physico-chemical properties of the soil used in the experiment.

Property	**Value**
Texture	Clay (52% clay, 29% silt, 19% sand)
pH(1:1 soil:water)	7.35
Electrical conductivity (EC), dS/m	1.25
Calcium carbonate ($CaCO_3$), %	10.5
Organic matter, %	1.15
Total nitrogen (N), %	0.06
Available phosphorus (P), mg/kg	5.26
Exchangeable potassium (K^+), mg/kg	395
Exchangeable calcium (Ca^{2+}), mg/kg	4268
Exchangeable magnesium (Mg^{2+}), mg/kg	624
Exchangeable sodium (Na^+), mg/kg	172

The experimental soil was classified as clay in texture, with a high clay content (52%), moderate salinity (EC 1.25 dS/m), and slightly alkaline pH (7.35). The soil contained low organic matter (1.15%) and total nitrogen (0.06%), indicating limited natural fertility. Available phosphorus (5.26 mg/kg) was particularly low, falling below optimal levels for tomato cultivation. Among exchangeable cations, calcium dominated the profile (4268 mg/kg), followed by magnesium (624 mg/kg), potassium (395 mg/kg), and sodium (172 mg/kg). These values suggest a calcareous soil with high Ca and moderate levels of Mg and K, but a somewhat imbalanced Ca:Mg ratio. The low organic matter and macronutrient levels underline the importance of organic amendment, such as vermicompost, to improve fertility and nutrient availability.

The nutrient composition and physico-chemical properties of the vermicompost used as an organic amendment in the experiment are summarized in Table 2.

Table 2. Physico-chemical properties of the vermicompost used in the experiment.

Property	**Value**
pH(1:1 soil:water)	7.50
Electrical conductivity (EC), dS/m	2.18
Organic matter, %	34.5
Total nitrogen (N) , %	1.52
Total phosphorus (P), %	0.46
Total potassium (K^+), %	2.85
Total calcium (Ca^{2+}), %	2.96
Total magnesium (Mg^{2+}), %	0.48

The vermicompost used in the study had a slightly alkaline pH (7.5) and moderate salinity (2.18 dS/m), typical of well-stabilized compost. It was rich in organic matter (34.5%), reflecting a high degree of humification and microbial activity during composting. Nutrient content analysis revealed that the vermicompost contained substantial amounts of macroelements, with total nitrogen at 1.52%, phosphorus at 0.46%, and potassium at 2.85%. In addition, it supplied essential secondary nutrients such as calcium (2.96%) and magnesium (0.48%).

These values indicate that the vermicompost was a nutrient-dense organic amendment capable of addressing the nutrient deficiencies of the experimental soil, particularly in terms of nitrogen and phosphorus. Furthermore, its high organic matter and cation content could contribute to improving soil structure, nutrient retention, microbial biomass, and enzymatic activities, especially under conditions of irrigation stress. Together with the soil characteristics previously described, the compositional quality of the vermicompost provides a strong rationale for the observed improvements in plant growth, yield, and soil biological and chemical parameters in the subsequent sections of this study.

Effects of Vermicompost and Irrigation Levels on Tomato Yield

Tomato yield per plant varied significantly depending on both vermicompost dose and irrigation level (Table 3). The highest yield (8.00 ± 0.20 kg/plant) was obtained in the V3I1 treatment (1.0 t/da vermicompost + 100% field capacity), whereas the lowest yield (4.90 ± 0.20 kg/plant) was recorded in the V0I3 treatment (no vermicompost + 50% field capacity).

Table 3. Effect of vermicompost doses and irrigation levels on tomato yield per plant (kg) under greenhouse conditions.

Treatment	**Yield (kg/plant)**
V0I1	6.50 ± 0.20
V0I2	5.70 ± 0.20
V0I3	4.90 ± 0.20
V1I1	7.00 ± 0.20
V1I2	6.20 ± 0.20
V1I3	5.40 ± 0.20
V2I1	7.50 ± 0.20
V2I2	6.70 ± 0.20
V2I3	5.90 ± 0.20
V3I1	8.00 ± 0.20
V3I2	7.20 ± 0.20
V3I3	6.40 ± 0.20
F-value	
V (vermicompost doses)	93.60***
I (irrigation levels)	219.57***
V x I	0.54 ^{ns}

*** p<0.001, ** p<0.01, * p<0.05, ^{ns} not significant

Under well-watered conditions (I1), increasing vermicompost dose steadily enhanced yield from 6.50 ± 0.20 kg/plant (V0I1) to 8.00 ± 0.20 kg/plant (V3I1). A similar pattern was observed under moderate (I2) and severe (I3) water deficit. For example, under I2, yield increased from 5.70 ± 0.20 (V0I2) to 7.20 ± 0.20 (V3I2); and under I3, from 4.90 ± 0.20 (V0I3) to 6.40 ± 0.20 (V3I3). This demonstrates that higher vermicompost doses improved yield even under limited water availability.

According to ANOVA results, both vermicompost ($F = 93.60$; $p < 0.001$) and irrigation level ($F = 219.57$; $p < 0.001$) had highly significant effects on tomato yield. The interaction between the two factors was not statistically significant ($F = 0.54$; $p > 0.05$), suggesting that their effects were largely independent and additive.

The yield results clearly indicate the strong influence of organic nutrient input and water availability on tomato productivity in greenhouse conditions. Vermicompost consistently increased tomato yield across all irrigation levels, highlighting its efficacy in enhancing soil fertility, nutrient supply, and possibly plant hormone stimulation. This can be attributed to the improved nutrient availability, microbial stimulation, and soil structure resulting from organic matter inputs, which in turn lead to enhanced root growth and nutrient uptake.

Water availability was another critical factor. Yields decreased with increasing water stress, consistent with well-documented physiological effects of drought on plant growth and fruit development. Water stress reduces cell expansion, impairs nutrient transport, and lowers photosynthetic activity, all of which negatively affect fruit size and number. However, the application of vermicompost partially mitigated the effects of water deficit, likely due to its water-holding capacity and promotion of a more active microbial population that facilitates nutrient mineralization even under suboptimal moisture conditions.

The absence of a significant interaction effect suggests that the influence of vermicompost on yield is stable across a range of irrigation conditions. This makes vermicompost a particularly valuable input for sustainable agriculture in semi-arid or controlled-environment systems, where water resources are often limited.

Previous studies have also shown similar trends. For example, Wang et al. (2017) and Hyder et al. (2015) reported improved yields in tomato and other vegetable crops with vermicompost applications, citing better nutrient efficiency and improved physiological resilience of plants. Our findings reinforce these conclusions, demonstrating that vermicompost application at 1.0 t/da is an effective strategy to maximize tomato yield, particularly when combined with adequate irrigation management.

Effects of Vermicompost and Irrigation on Leaf Nutrient Contents of Tomato Plants

Leaf nutrient contents of tomato plants were significantly affected by both vermicompost application and irrigation regimes (Table 4).

Leaf nitrogen content increased significantly with increasing vermicompost dose and was also affected by irrigation level. The highest N concentration (3.0 ± 0.10%) was observed under V3I1 (1.0 t/da vermicompost, full irrigation), while the lowest value (2.2 ± 0.10%) occurred in the control treatment under severe water stress (V0I3). ANOVA results confirmed a significant main effect of vermicompost ($F = 73.48$; $p < 0.001$) and a moderate effect of irrigation ($F = 3.88$; $p < 0.05$). However, the interaction between the two was not significant ($F = 0.29$; $p > 0.05$).

Phosphorus concentration in leaves also showed a strong positive response to vermicompost application, ranging from 0.0 ± 0.14% (V0I3) to 0.8 ± 0.13% (V3I1). Irrigation level had a highly significant effect ($F = 24.86$; $p < 0.001$), and phosphorus was the most sensitive nutrient to water deficit. ANOVA revealed a significant main effect of vermicompost ($F = 109.13$; $p < 0.001$) but no interaction effect ($F = 0.71$; $p > 0.05$).

Leaf K content increased from 2.4 ± 0.14% in V0I3 to 3.2 ± 0.09% in V3I1. Both vermicompost ($F = 58.07$; $p < 0.001$) and irrigation ($F = 5.83$; $p < 0.05$) had significant effects on potassium accumulation, although the interaction term remained non-significant ($F = 0.89$; $p > 0.05$).

Calcium content in leaves was influenced by both factors. The Ca content increased from 1.3 ± 0.05% (V0I3) to 2.1 ± 0.14% (V3I1). ANOVA results indicated significant effects of vermicompost ($F = 93.73$; $p < 0.001$) and irrigation ($F = 7.87$; $p < 0.01$), with no significant interaction ($F = 0.75$; $p > 0.05$).

Magnesium levels ranged from 0.1 ± 0.14% (V0I3) to 0.9 ± 0.08% (V3I1). Both vermicompost ($F = 66.07$; $p < 0.001$) and irrigation ($F = 10.79$; $p < 0.01$) had strong effects, with magnesium showing a substantial decrease under water stress. Again, no significant interaction was observed ($F = 0.88$; $p > 0.05$).

Table 4. Leaf nutrient contents (N, P, K, Ca, Mg) of tomato plants as affected by different vermicompost doses and irrigation levels.

Treatment	Leaf N (%)	Leaf P (%)	Leaf K (%)	Leaf Ca (%)	Leaf Mg (%)
V0I1	2.4 ± 0.12	0.2 ± 0.15	2.6 ± 0.14	1.5 ± 0.14	0.3 ± 0.09
V0I2	2.3 ± 0.09	0.1 ± 0.07	2.5 ± 0.08	1.4 ± 0.08	0.2 ± 0.06
V0I3	2.2 ± 0.10	0.0 ± 0.14	2.4 ± 0.14	1.3 ± 0.05	0.1 ± 0.14
V1I1	2.6 ± 0.06	0.4 ± 0.13	2.8 ± 0.13	1.7 ± 0.05	0.5 ± 0.09
V1I2	2.5 ± 0.13	0.3 ± 0.14	2.7 ± 0.06	1.6 ± 0.10	0.4 ± 0.09
V1I3	2.4 ± 0.12	0.2 ± 0.12	2.6 ± 0.14	1.5 ± 0.14	0.3 ± 0.13
V2I1	2.8 ± 0.07	0.6 ± 0.13	3.0 ± 0.12	1.9 ± 0.12	0.7 ± 0.11
V2I2	2.7 ± 0.08	0.5 ± 0.05	2.9 ± 0.11	1.8 ± 0.07	0.6 ± 0.13
V2I3	2.6 ± 0.09	0.4 ± 0.06	2.8 ± 0.06	1.7 ± 0.12	0.5 ± 0.11
V3I1	3.0 ± 0.10	0.8 ± 0.13	3.2 ± 0.09	2.1 ± 0.14	0.9 ± 0.08
V3I2	2.9 ± 0.15	0.7 ± 0.13	3.1 ± 0.06	2.0 ± 0.10	0.8 ± 0.13
V3I3	2.8 ± 0.05	0.6 ± 0.06	3.0 ± 0.13	1.9 ± 0.11	0.7 ± 0.10
F-value					
V (vermicompost doses)	73.48***	109.13***	58.07***	93.73***	66.07***
I (irrigation levels)	3.88 ns	24.86***	5.83 ns	7.87 ns	10.79 ns
V x I	0.29 ns	0.71 ns	0.89 ns	0.75 ns	0.88 ns

*** p<0.001, ** p<0.01, * p<0.05, ns not significant

The findings clearly demonstrate that vermicompost significantly improves the nutrient status of tomato plants. The increase in leaf nitrogen, phosphorus, potassium, calcium, and magnesium concentrations with increasing vermicompost dose reflects the enhanced nutrient supply, mineralization rate, and microbial activity commonly associated with organic amendments. Vermicompost provides a slow-release source of nutrients and contributes to improved cation exchange capacity, thus facilitating greater nutrient retention and uptake by plants.

Among the measured nutrients, phosphorus and magnesium appeared most sensitive to irrigation levels, suggesting that water availability plays a critical role in their mobility and root absorption. This aligns with previous findings that under water-deficit conditions, reduced soil moisture limits nutrient diffusion and uptake, particularly for elements like P and Mg which rely on mass flow and diffusion mechanisms.

The lack of significant interaction between vermicompost and irrigation across all nutrients indicates that vermicompost's beneficial effects on nutrient accumulation were robust and relatively independent of soil moisture level. This stability underscores its potential as a soil amendment in regions prone to water stress.

These results support earlier studies (Yang et al., 2015; Wang et al., 2017) showing that vermicompost not only enhances nutrient availability but also contributes to physiological functions such as chlorophyll synthesis (via N and Mg), energy transfer (via P), and membrane integrity (via K and Ca). In practical terms, the combined improvement in macro-element nutrition likely underpins the increased yield and resilience observed in tomato plants treated with vermicompost, even under moderate to severe irrigation stress.

Effects of Vermicompost and Irrigation on Post-Harvest Soil Nutrient Status

The results demonstrated that vermicompost application significantly improved soil nutrient availability after tomato harvest, particularly for nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg), whereas the effect on calcium (Ca) was not statistically significant (Table 5).

Post-harvest soil nitrogen levels increased significantly with vermicompost dose. The highest available N (60 ± 2.7 mg/kg) was measured under the V3I1 treatment, while the lowest (39 ± 1.6 mg/kg) occurred in the control under severe stress (V0I3). According to ANOVA results, vermicompost ($F = 76.42$; $p < 0.001$) and irrigation ($F = 22.03$; $p < 0.001$) had highly significant effects on available nitrogen, while their interaction was not significant ($F = 1.81$; $p > 0.05$).

Soil available phosphorus followed a similar pattern, ranging from 2 ± 0.1 mg/kg (V0I3) to 23 ± 1.1 mg/kg (V3I1). Vermicompost application resulted in a pronounced increase ($F = 253.24$; $p < 0.001$), and phosphorus was the most irrigation-sensitive nutrient in this group ($F = 79.06$; $p < 0.001$). The interaction between the two factors was not significant ($F = 0.11$; $p > 0.05$).

Exchangeable K increased moderately with vermicompost (from 134 ± 7.8 to 155 ± 5.8 mg/kg), but was less sensitive to irrigation differences. ANOVA revealed a significant effect of vermicompost ($F = 16.22$; $p < 0.001$) but not irrigation ($F = 2.37$; $p > 0.05$) or their interaction ($F = 1.29$; $p > 0.05$).

Calcium levels in the soil showed minimal variation across treatments, with values ranging from 794 ± 35.0 mg/kg to 815 ± 47.8 mg/kg. Neither vermicompost ($F = 0.61$; $p = 0.617$) nor irrigation ($F = 2.53$; $p > 0.05$) significantly affected Ca availability, and the interaction was also not significant ($F = 0.33$; $p > 0.05$).

Magnesium content was positively affected by vermicompost, increasing from 104 ± 5.5 mg/kg (V0I3) to 125 ± 6.3 mg/kg (V3I1). Both vermicompost ($F = 26.79$; $p < 0.001$) and irrigation ($F = 3.53$; $p < 0.05$) had statistically significant effects, while their interaction was not significant ($F = 0.20$; $p > 0.05$).

Table 5. Post-harvest soil nutrient contents (available N, P and exchangeable K, Ca, Mg) as affected by vermicompost doses and irrigation levels.

Treatment	Available N (mg/kg)	Available P (mg/kg)	Exchangeable K (mg/kg)	Exchangeable Ca (mg/kg)	Exchangeable Mg (mg/kg)
V0I1	45 ± 2.5	8 ± 0.4	140 ± 5.0	800 ± 25.1	110 ± 5.8
V0I2	42 ± 1.9	5 ± 0.2	137 ± 7.7	797 ± 32.0	107 ± 5.6
V0I3	39 ± 1.6	2 ± 0.1	134 ± 7.8	794 ± 35.0	104 ± 5.5
V1I1	50 ± 2.0	13 ± 0.5	145 ± 8.4	805 ± 39.8	115 ± 4.4
V1I2	47 ± 1.6	10 ± 0.5	142 ± 6.3	802 ± 25.5	112 ± 5.3
V1I3	44 ± 1.4	7 ± 0.4	139 ± 8.3	799 ± 43.6	109 ± 3.9
V2I1	55 ± 3.0	18 ± 0.8	150 ± 5.6	810 ± 42.4	120 ± 6.9
V2I2	52 ± 2.0	15 ± 0.6	147 ± 5.6	807 ± 35.0	117 ± 4.7
V2I3	49 ± 1.7	12 ± 0.4	144 ± 8.6	804 ± 45.7	114 ± 4.5
V3I1	60 ± 2.7	23 ± 1.1	155 ± 5.8	815 ± 47.8	125 ± 6.3
V3I2	57 ± 2.7	20 ± 0.9	152 ± 8.1	812 ± 26.4	122 ± 4.7
V3I3	54 ± 3.1	17 ± 0.5	149 ± 7.8	809 ± 41.6	119 ± 4.8
F-value					
V (vermicompost doses)	76.42***	253.24***	16.22***	0.61 ns	26.79***
I (irrigation levels)	22.03***	79.06***	2.37 ns	2.53 ns	3.53 ns
V x I	1.81 ns	0.11 ns	1.29 ns	0.33 ns	0.20 ns

*** p<0.001, ** p<0.01, * p<0.05, ns not significant

The results reveal that vermicompost significantly enhanced the post-harvest nutrient status of the soil, especially with respect to nitrogen, phosphorus, potassium, and magnesium. These improvements are attributed to the nutrient-rich composition of vermicompost, its slow mineralization rate, and its positive influence on soil microbial activity and organic matter content. As organic matter decomposes, it releases essential nutrients and stimulates microbial-driven nutrient cycling processes, improving soil fertility over time.

Among the nutrients studied, available phosphorus exhibited the most pronounced increase with vermicompost and was also highly sensitive to irrigation regime. This is expected, as phosphorus availability in soils is influenced by both organic matter inputs and moisture levels that affect solubility and diffusion. Similarly, available nitrogen was significantly influenced by both factors, likely due to increased mineralization and microbial nitrification promoted by vermicompost under moist conditions.

In contrast, exchangeable calcium remained largely unchanged across treatments. This may be due to the already high background levels of Ca in the experimental soil or the relatively lower mobility of calcium ions, which are less responsive to short-term organic inputs or irrigation changes.

The observed increases in potassium and magnesium reflect the contributions of vermicompost as a source of these cations and its ability to improve cation exchange capacity (CEC). Potassium availability was less responsive to irrigation stress, suggesting its retention in the soil exchange complex, while magnesium showed moderate sensitivity, consistent with its higher mobility.

The absence of significant interaction effects across all nutrients indicates that vermicompost's contribution to soil nutrient enrichment was consistent and stable, regardless of irrigation levels. This implies that vermicompost is a reliable amendment for enhancing soil fertility even under water-limited conditions.

These findings are consistent with previous literature, which emphasizes that vermicompost can improve soil physicochemical properties, increase nutrient retention, and buffer against nutrient losses during periods of water stress (Hyder et al., 2015; Yang et al., 2015). Therefore, integrating vermicompost into nutrient management programs offers a sustainable strategy to improve soil health and maintain productivity in protected cultivation systems.

Effects of Vermicompost and Irrigation on Post-Harvest Soil Biological Properties

Post-harvest soil biological properties were significantly influenced by both vermicompost application and irrigation regime (Table 6).

Microbial biomass carbon (MBC) increased significantly with increasing vermicompost doses. The highest value (180 ± 10.5 µg C/g soil) was recorded in the V3I1 treatment, while the lowest (134 ± 4.9 µg C/g soil) was found in V0I3. ANOVA indicated significant effects of both vermicompost ($F = 31.16$; $p < 0.001$) and irrigation ($F = 8.80$; $p < 0.01$), with no significant interaction ($F = 0.52$; $p > 0.05$).

Basal soil respiration (BSR) followed a similar pattern, rising from 29 ± 1.6 mg CO_2-C/kg/day (V0I3) to 75 ± 4.0 mg CO_2-C/kg/day (V3I1). ANOVA results confirmed significant main effects of vermicompost ($F = 151.34$; $p < 0.001$) and irrigation ($F = 86.53$; $p < 0.001$), with no significant interaction ($F = 1.38$; $p > 0.05$).

Dehydrogenase activity (DHA), a marker of overall microbial oxidative metabolism, showed a strong positive response to vermicompost and irrigation. Activity increased from 14 ± 0.8 µg TPF/g soil/h in V0I3 to 60 ± 3.1 µg TPF/g soil/h in V3I1. ANOVA results demonstrated significant effects for vermicompost ($F = 353.93$; $p < 0.001$) and irrigation ($F = 176.03$; $p < 0.001$), and notably, a significant interaction effect was observed ($F = 3.82$; $p < 0.01$).

Catalase activity (CA) also increased with vermicompost application, from 2.2 ± 0.22 mL O_2/g soil 3min (V0I3) to 5.1 ± 0.15 (V3I1). Both vermicompost ($F = 209.20$; $p < 0.001$) and irrigation ($F = 65.38$; $p < 0.001$) significantly affected catalase activity, while the interaction term was not significant ($F = 1.52$; $p > 0.05$).

Urease activity (UA) rose steadily with higher vermicompost doses and better irrigation, ranging from 4 ± 0.2 µg N/g soil/h (V0I3) to 50 ± 1.9 µg N/g soil/h (V3I1). ANOVA revealed highly significant effects of vermicompost ($F = 351.12$; $p < 0.001$) and irrigation ($F = 203.31$; $p < 0.001$), with no significant interaction ($F = 0.51$; $p > 0.05$).

Table 6. Post-harvest soil microbial biomass carbon (MBC), soil respiration, and enzyme activities (dehydrogenase, catalase, urease) as influenced by vermicompost doses and irrigation levels.

Treatment	**MBC**	**BSR**	**DHA**	**CA**	**UA**
V0I1	150 ± 4.6	45 ± 1.4	30 ± 1.0	3.0 ± 0.14	20 ± 0.7
V0I2	142 ± 6.7	37 ± 1.5	22 ± 1.0	2.6 ± 0.18	12 ± 0.6
V0I3	134 ± 4.9	29 ± 1.6	14 ± 0.8	2.2 ± 0.22	4 ± 0.2
V1I1	160 ± 7.6	55 ± 3.2	40 ± 2.3	3.7 ± 0.29	30 ± 1.0
V1I2	152 ± 4.8	47 ± 2.5	32 ± 1.7	3.3 ± 0.30	22 ± 0.9
V1I3	144 ± 6.2	39 ± 1.2	24 ± 0.9	2.9 ± 0.20	14 ± 0.6
V2I1	170 ± 9.6	65 ± 2.0	50 ± 1.9	4.4 ± 0.24	40 ± 1.4
V2I2	162 ± 6.7	57 ± 2.6	42 ± 1.3	4.0 ± 0.16	32 ± 1.5
V2I3	154 ± 6.4	49 ± 2.9	34 ± 1.8	3.6 ± 0.19	24 ± 1.4
V3I1	180 ± 10.5	75 ± 4.0	60 ± 3.1	5.1 ± 0.15	50 ± 1.9
V3I2	172 ± 7.6	67 ± 3.0	52 ± 2.0	4.7 ± 0.21	42 ± 2.2
V3I3	164 ± 7.7	59 ± 2.2	44 ± 2.6	4.3 ± 0.27	34 ± 1.5
F-value					
V (vermicompost doses)	31.16***	151.34***	353.93***	209.20***	351.12***
I (irrigation levels)	8.80 ^{ns}	86.53***	176.03***	65.38***	203.31***
V x I	0.52 ^{ns}	1.38 ^{ns}	3.82 ^{ns}	1.52 ^{ns}	0.51 ^{ns}

MBC: Microbial biomass carbon, µg C/g soil ; BSR: Basal soil respiration, mg CO_2-C/kg/day ; DHA: Dehydrogenase activity, µg TPF/g soil/h ; CA: Catalase activity, mL O_2/g soil 3min; UA: Urease activity, µg N/g soil/h
*** p<0.001, ** p<0.01, * p<0.05, ^{ns} not significant

The data clearly demonstrate that vermicompost is a potent enhancer of soil microbial activity and enzymatic functioning. Across all parameters—MBC, BSR, DHA, CA, and UA—significant increases were observed with increasing vermicompost doses. These improvements are attributed to the input of organic carbon and nutrients that serve as substrates for microbial growth and metabolism. Vermicompost is rich in humic substances, growth-promoting hormones, and labile carbon, all of which stimulate microbial proliferation and enzymatic activity.

The observed increase in MBC and BSR reflects heightened microbial biomass and metabolic activity. Higher respiration rates suggest enhanced decomposition processes and nutrient turnover, which contribute to improved soil fertility (Smith and Paul, 1990; Meli et al., 2002; Kızılkaya et al., 2004). Enzyme activities (DHA, CA, UA) provide further evidence of improved microbial functioning and biochemical potential of the soil (Gong, 1997; Pascual et al., 1998; Obbard, 2001; Kızılkaya, 2008; Durmuş and Kızılkaya, 2022; Toor et al., 2024).

Among these, DHA not only showed the greatest relative increase but also exhibited a significant interaction between vermicompost and irrigation. This suggests that microbial redox processes are particularly sensitive to water availability, and the stimulating effect of vermicompost on dehydrogenase may be more pronounced under adequate moisture conditions.

CA, involved in reactive oxygen species detoxification, and urease activity, which reflects N transformation capacity, were both significantly enhanced by vermicompost. These responses indicate improved oxidative balance and nitrogen cycling in the rhizosphere, essential for healthy root function and nutrient availability.

Water stress consistently reduced all biological indicators, underscoring the sensitivity of microbial systems to moisture availability. However, even under the most severe stress (I3), soils treated with higher vermicompost doses maintained relatively higher biological activity compared to untreated soils, demonstrating vermicompost's buffering capacity.

These results are consistent with previous findings indicating that organic amendments, particularly vermicompost, enhance microbial resilience and enzymatic activity under abiotic stress (Anderson, 1982; Wang et al., 2017). In water-limited systems, this functional stability is crucial for sustaining nutrient cycling and supporting plant productivity.

Conclusion

This study demonstrated that both vermicompost application and irrigation level significantly affect tomato yield, plant nutrient uptake, and soil fertility under greenhouse conditions. Vermicompost applied at increasing doses (0.25, 0.5, and 1.0 t/da) consistently improved tomato yield per plant, with the highest yield (8.00 ± 0.20 kg/plant) observed at the 1.0 t/da dose under full irrigation (100% field capacity). Yield declined under water deficit, but the negative effects of stress were partially mitigated by higher vermicompost doses.

Leaf nutrient contents (N, P, K, Ca, Mg) were significantly enhanced by vermicompost, with phosphorus and magnesium being particularly sensitive to water stress. Post-harvest soil analyses indicated that vermicompost substantially increased available N, P, and exchangeable K and Mg contents, while Ca levels remained unaffected. Soil biological properties, including microbial biomass carbon, soil respiration, and enzyme activities (dehydrogenase, catalase, urease), also improved significantly with vermicompost and were generally reduced under irrigation stress.

Among all parameters studied, phosphorus availability and dehydrogenase activity were most responsive to the combined effects of nutrient and water management. The absence of significant interaction effects for most variables suggests that the positive effects of vermicompost are consistent across irrigation regimes.

In conclusion, vermicompost application at 1.0 t/da is a promising organic fertilization strategy that enhances tomato productivity, improves plant nutrient status, and promotes soil biological health. Its beneficial effects are evident even under moderate to severe water stress, making it a valuable tool for sustainable greenhouse cultivation in water-limited environments. Further research under open-field conditions and with different crop species could help validate and expand these findings for broader agroecological application.

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Biochar application enhances soil nutrient availability and microbial biomass in Chernozemic soil

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Abstract

Field research was conducted for two years to evaluate the effect of corn straw biochar on soil chemical properties and microbial biomass of Chernozemic soil in Northern Province, China. The research set up was randomized complete block design with three replicates. A one-time application of biochar was done with the use of ploughing machine to a depth of 20 cm in the first year without further application in the second year. Each treatment plot size was 25 m^2. Biochar (BC) was applied at three doses: control (BC0), 15 (BC15), and 30 (BC30) t ha^{-1}. The doses of biochar significantly increased soil organic carbon (SOC), soil pH, the available nitrogen (AN), phosphorus (AP), and potassium (AK) as compared to the plots with no biochar additions (control) in 0-15 and 15-30 cm soil depth. Biochar at 30 t ha^{-1} (BC30) relatively increased soil organic carbon (SOC), available nitrogen (AN), phosphorus (AP), and potassium (AK) in 0-15 and 15-30 cm in both years than biochar at 15 t ha^{-1}(BC15). Soil pH increased in the first year compared to the control while no significant changes was noticed in the succeeding year. Biochar incorporation resulted in considerable increases in soil microbial biomass carbon (MBC), nitrogen (MBN) and phosphorus (MBP) in 0-15 and 15-30 cm soil depth in both years. Overall, the results of this study suggested that highest dose of corn straw biochar (30 t ha^{-1}) could enhance restoration of soil health by boosting soil nutrients availability and enhancing microbial activities in Chernozemic soils.

Keywords: Biochar, available nutrients, microbial biomass pool, Chernozemic soil.

Introduction

Considerable attention has been given to the use of organic additives which is one of the known ways of improving soil health and promoting agricultural sustainability. These additives can enrich soil with nutrients and stimulate microbial activity, particularly in soils with low organic matter content (Khadem and Raiesi, 2017a). The organic additives like biochar, animal waste, homemade waste, green amendments and industrial waste have continuously become an indispensable source of nutrients in the soil (Mohanty et al., 2013; Ali et al., 2011; Quilty and Cattle, 2011). Their contributions have supported the increasing demand for global food to a reasonable extent. Among these, a carbon enriched product known as "biochar" continues to stand out as an amendment of potential multiple benefits (Song et al., 2018; Zhang et al., 2019). More so, its response to utilization can be related to production conditions and biomass source. The efficacy of biochar is generally reflected in its ability to improve soil properties (Luo et al., 2020). Unlike, other organic additives, the use of biochar has generated sustained interest over the years due to its long-term promising effects of C sequestration (Wang et al., 2017a,b). Periodically, it has mostly been presented to improve properties of various soils, including tropical sandy soils (Harter et al., 2014); chromic luvisol (Luo et al., 2013); albic soil (Joseph et al., 2019) and phaeozemic soil (Zhao et al., 2020). Furthermore, biochar contains essential nutrients including nitrogen (N), phosphorus (P) and potassium (K), which are gradually released into the soil (Ouyang et al., 2014). More so, its chemical and structural composition differs glaringly (Wu et al., 2019). Despite the component differences in biochar, assessible improvement has been

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uncovered in the utilization of biochar as soil amendment. The prolonged use of biochar has been linked to increased microbial biomass (Ameloot et al., 2013), improved soil quality (Sohi, 2012), greater nutrient availability (Herrmann et al., 2019), and also limit greenhouse gas emissions from the soil (Li et al., 2015). On the other hand, the usage of biochar to restore unhealthy soils is rising, availing more lands for cultivation (Alling et al., 2014; Berihun et al., 2017) and boosting crop yields (Barrow, 2012). Historically, the intensive pressure on agricultural lands has led to severe disruption in the soil system in many parts of the world (Xu et al., 2010). And drastically lower the total area of fertile lands, leading due to natural disasters and human-induced activities (Mulcahy et al., 2013). As foretold by Lal (2010), soil degradation might cause deterioration in food supply and trigger more competition for agricultural land.

Chernozemic soils, described by WRB (2015) as humus-rich, highly fertile black soils, are widespread in Northeast China and serve as a crucial agricultural base. However, their fertility has declined over time due to intensive farming and other human activities. While many studies have explored the effects of biochar on various soil types, its impact on Chernozemic soils remains limited (Zharlygassov et al., 2025). The aim of this study is to examine the effect of corn straw biochar on soil chemical and microbial properties of Chernozemic soil. We hypothesized that corn straw biochar at an increasing level would lead to enhanced soil nutrient availability, and improve microbial activities while maintaining soil health.

Material and Methods

Research Site

The field research was conducted at the Heilongjiang Bayi Agricultural University Research Station, Daqing City, Heilongjiang Province, Northeast China (latitude 46° 58' N, longitude 125° 03' E). It is situated in the northern temperate continental monsoon climate. The annual mean temperature and precipitation is about 4.5 °C and 509 mm respectively. The soil properties prior to amendment show that soil is silty clay (26.2% sand, 31.4% silt and 42.4% clay) and Haplic Chernozem as per the soil taxonomy of World Reference Base for Soil Resources (WRB, 2015). The basic properties of soil are presented in Table 1.

Table 1. Prior soil measurements

Soil Depth (cm)	SOC (g kg^{-1})	AN	AP (mg kg^{-1})	AK	pH	Cu	Mn (mg kg^{-1})	Fe	Zn
0-15cm	17.51	1.51	50.08	112.86	8.2	1.82	1.88	2.24	1.05
15-30cm	15.31	1.33	48.21	105.12	8.0	1.91	1.12	1.56	0.89

*SOC= soil organic carbon; AN= available nitrogen; AP= available phosphorus; AK=available potassium; Cu=copper; Mn= manganese; Fe= iron; Zn=zinc

Experimental set up, Treatment application and Soil sample collection

The first experimental year was from April to October 2017 as well as the second year which was also from April to October 2018. The site was ploughed, harrowed and divided into plots. Three replicated plots of sizes 5 by 5 m^2 (25 m^2), with protective rows of 0.5 m in width and laid out in randomized complete block design. Thereafter, loads of biochar were spread on the surface at 0, 15 and 30 t ha^{-1}, and thoroughly mixed into the top 0-20 cm layer of the soil with the aid of a ploughing machine and with no supplementary additives in the following year. These treatments were assigned as control (BC0), BC15 (15 t ha^{-1}) and BC30 (30 t ha^{-1}) prior to maize planting (Maize ZD 958). The initial and post-harvest soil samples were randomly collected at the upper (0-15 cm) and lower (15-30 cm) soil depth using soil auger and core, packed in air-tight bags and taken to the laboratory. A part of the collected soil samples was immediately stored at 4 °C to determine the contents of microbial biomass C, N and P. Later, air-dried, passed through a 2 mm sieve and stored at room temperature for determination of physical and chemical properties.

Biochar

The corn-straw derived biochar utilized in this research study, pyrolyzed at 800 ºC using an industrial autothermic regulated pyrolyser with oxygen-limited conditions, was locally purchased from Sanli New Energy Company, China. Biochar characteristics were sorted by Bao (2000), and Jones and Willett (2006) procedures for pyrolyzed biomass. Carbon (C), hydrogen (H) and nitrogen (N) were determined by using Elemental Analyzer (EURO EA 3000). The biochar nutrient contents were: C (63.85%), H (2.76%), available nutrients N (1.57 %), P (1.89 %), K (1.32 %), and pH (10.09).

Analytical methods for soil samples

Soil organic carbon (SOC) was estimated by wet oxidation according to Walkley and Black (1934). The soil pH was measured by soil/water at 1:2 suspension using pH meter (Richards, 1954). Available Nitrogen (AN), Phosphorus (AP) and Potassium (AK) concentration were sorted by potassium permanganate method

(Subbiah and Asija, 1956), 0.5 M sodium bicarbonate (Olsen and Sommers, 1982), and 1 M ammonium acetate (Helmke and Sparks, 1996) methods, respectively. Soil texture was sorted by hydrometer method (Gavlak et al., 2003). Micronutrients was sorted by DTPA method (Lindsay and Norrvell, 1978).

Microbial biomass measurement

Soil microbial biomass carbon (MBC) and nitrogen (MBN) were measured using a chloroform fumigation direct extraction procedure (Brookes et al., 1985; Vance et al., 1987). Aliquot of extracts were analysed for MBC using an automated TOC Analyzer (Shimadzu, TOC-500 China) and MBN was determined using the Kjeldahl method. Microbial biomass Phosphorus (MBP) was determined with the anion exchange resin method (Kouno et al., 1995).

Data analysis

The collated data was first arranged in MS excel before been subjected to analysis of variance using GenStat software (version 10.3.0.0 VSN International Ltd). Tukey post-hoc test ($P < 0.05$) was used for comparison of means.

Results

Soil nutrient as affected by biochar

In the first year (2017), biochar increased soil organic carbon contents in accordance with increase in application doses of biochar additives. Treatment BC15 and BC30 elevated SOC in 0-15 cm soil depth compared with BC0 (control), whereas, at 15-30 cm soil depth, BC30 was significantly higher, followed by BC15 when compared with BC0 (Figure 1). In the second year (2018), similar case was observed at both 0-15 and 15-30 cm soil depths. BC30 was notably higher in soil organic carbon, followed by BC15 which were both significantly higher than BC0 respectively.

In the first year, BC15 and BC30 did not show significant effect but contributed increases to the soil pH in 0-15 cm soil depth compared with control, whereas, at 15-30 cm soil depth, similar resulting effects were observed (Figure 1). In the second year, and contrarily, BC15 and BC30 treatments did not contribute differences in 0-15 and 15-30 cm soil depth, compared with control.

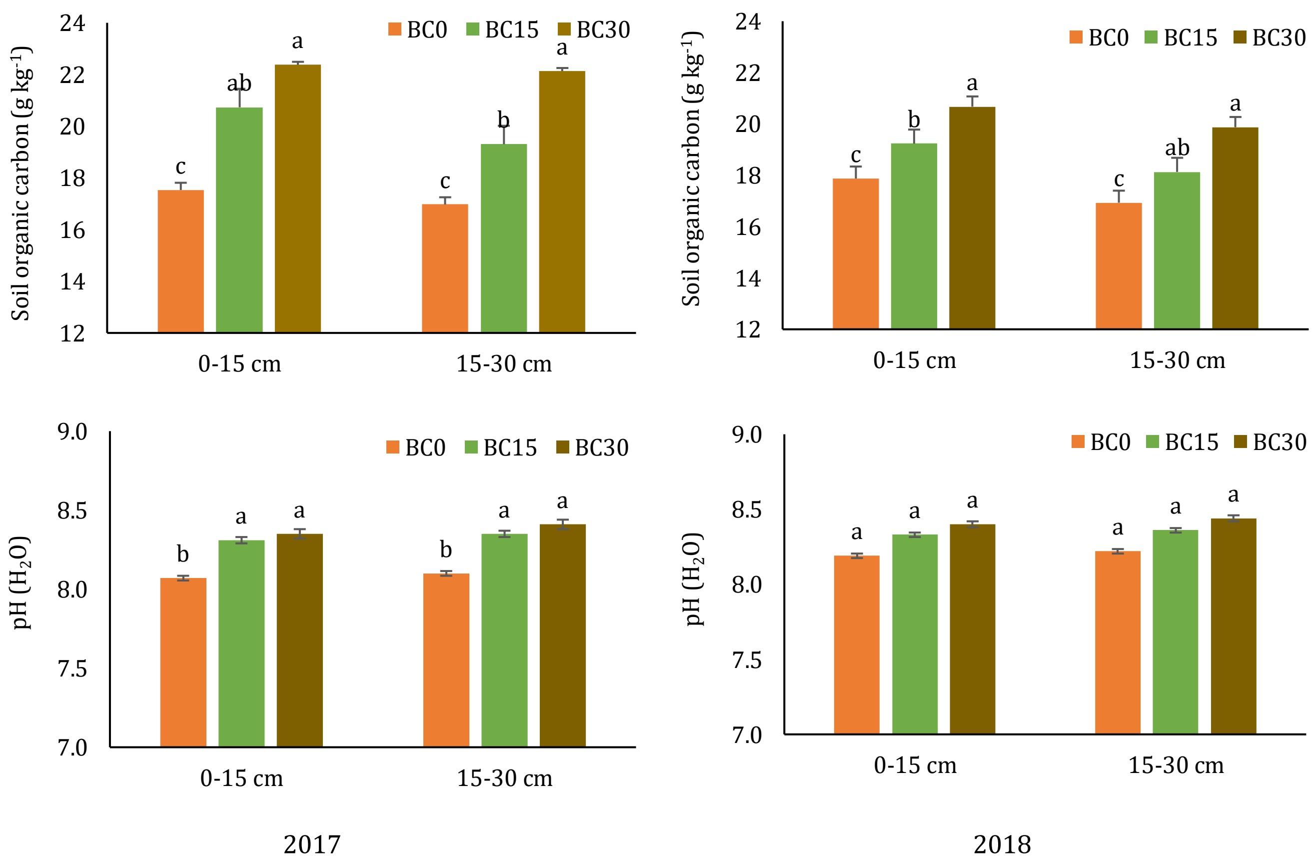

Figure 1. Effects of biochar on soil organic carbon and soil pH in 0-15 and 15-30 cm soil depth in 2017 (left) and 2018 (right). Different alphabets correspond to significant differences as regard Tukey post hoc test ($P < 0.05$).

The available nutrient contents (AN, AP and AK) are delineated in Figure 2. In the first year, the biochar treatments (BC15 and BC30) slightly differ in concentration of AN in 0-15 cm soil depth, compared with control, whereas, at 15-30 cm soil depth, BC30 was greatly higher followed by BC15, compared with control. In the second year, BC15 and BC30 statistically differ compared with control, whereas, at 15-30 cm depth, the biochar doses did not exhibit any notable effect compared to BC0 (Figure 2).

In the first year, biochar with highest dose (BC30) influenced an increase in concentration of AP in 0-15 cm soil depth compared to the lower dose (BC15) and control (Figure 2), whereas, in 15-30 cm soil depth, the two doses of application did not differ statistically but emerged higher than BC0 (control). In the second year, BC15 and BC30 did not exhibit significant differences in 0-15 cm soil depth but higher than the control, whereas, at 15-30 cm soil depth, similar treatment pattern was noticed.

In the first year, BC15 and BC30 treatments showcased notable differences in concentration of AK in 0-15 cm soil depth, compared with control, whereas, in 15-30 cm soil depth, BC30 was significantly higher than BC15 compared with control (Figure 2). In the second year, both doses of biochar treatments significantly differ compared to BC0 in 0-15 cm soil depth, whereas, in 15-30 cm soil depth, BC30 emerged higher than BC15 compared with control.

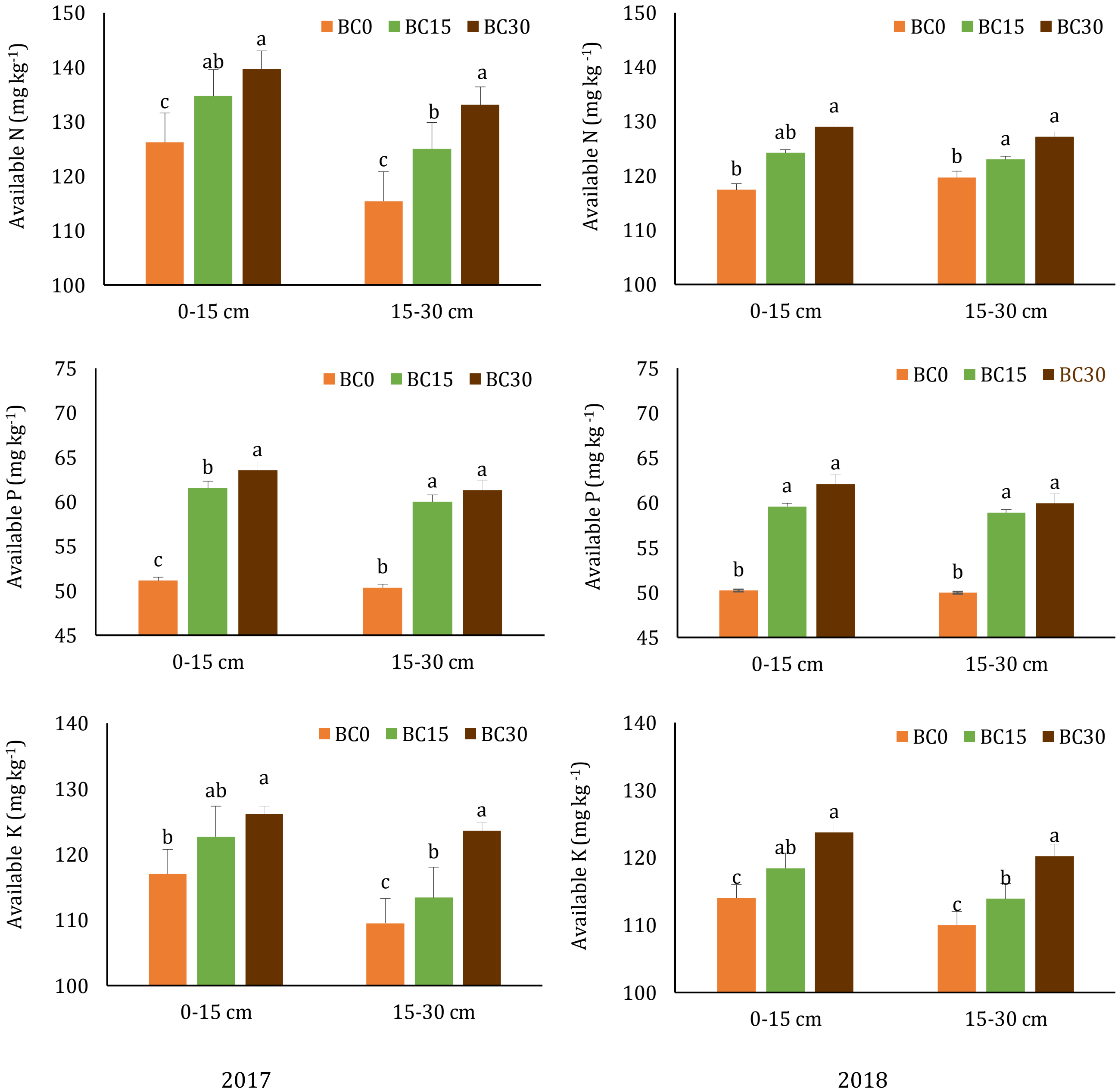

Figure 2. Effects of biochar on soil in 0-15 and 15-30 cm soil depth in 2017 (left) and 2018 (right). Different alphabets correspond to significant differences as regard Tukey post hoc test (P < 0.05)

Changes in soil microbial biomass

In the first year, BC15 and BC30 biochar treatments statistically surpassed control (BC0) in 0-15 cm soil depth, for MBC (Figure 3), whereas, in 15-30 cm soil depth, the highest dose exhibited (BC30) a statistically higher value than the reduced dose of biochar treatment (BC15) in 0-15 cm soil depth compared to control. In the second year, both doses of treatments (BC15 and BC30) showcased higher differences for MBC, in 0-15 cm soil depth, compared with control. Similarly, in 15-30 cm soil depth, pattern of treatment exhibition did not differ.

In the first year, the highest and lowest dose of biochar (BC30 and BC15) statistically increased MBN in 0-15 cm soil depth, compared to BC0, respectively (Figure 3) whereas, in 15-30 cm soil depth, treatment BC30 emerged higher, and followed by BC15, compared with control. In the second year, BC15 and BC30 did not differ but was significantly higher in MBN compared with control in 0-15 cm soil depth, whereas, in 15-30 cm soil depth, the highest addition of biochar dose (BC30) was greatly higher, followed by BC15, compared with control.

In the first year, BC15 and BC30 doses did not significantly differ but both higher in MBP, in 0-15 cm soil depth, compared with control (Figure 3), whereas, in 15-30 cm soil depth, BC30 surpassed BC15, compared with BC0. In the second year, BC15 and BC30 was higher in 0-15 cm soil depth, compared with control, whereas, in 15-30 cm soil depth, BC30 significantly increased than BC15, compared with control.

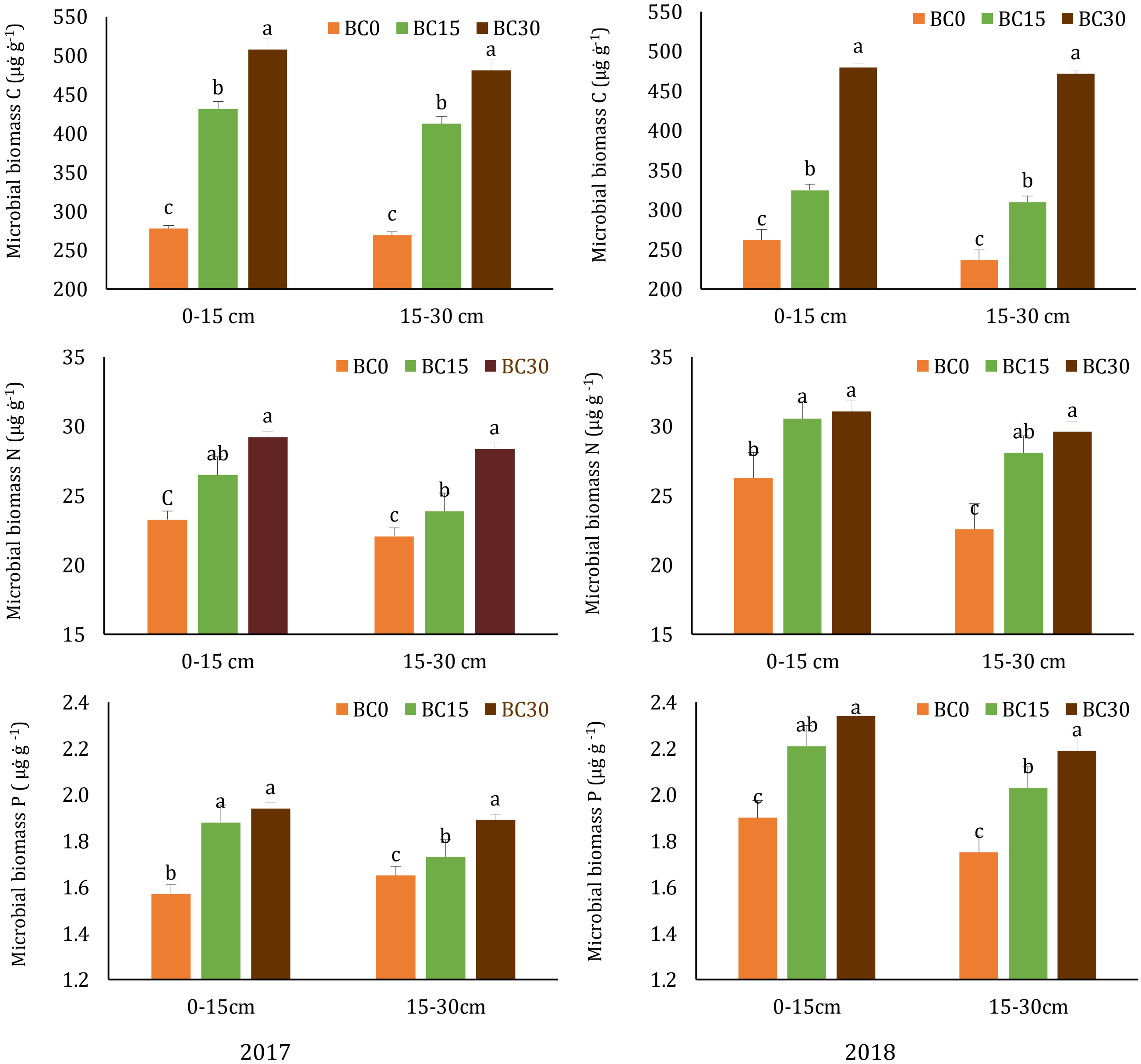

Figure 3. Effects of biochar on microbial biomass carbon (MBC), nitrogen (MBN) and phosphorus (MBP) in 0-15 and 15-30 cm soil depth in 2017 (left) and 2018 (right). Different alphabets correspond to significant differences as regard Tukey post hoc test (P < 0.05)

Discussion

Soil nutrients dynamics

Amending soils with biochar has been helpful in overcoming nutrient shortages (Khorram et al. 2018; El-Naggar et al., 2019). Relative changes were noticed in the soil pH at both 0-15 and 15-30 cm soil depth due to biochar influence. This is congruent with previous studies that have reported biochar contains ash, especially cations which may offer an effective change in pH of biochar treated soils (Doan et al., 2015; Vaccari et al., 2015). In support, acidic compounds produced on biochar surface through the oxidation of biochar particles in the soil could also be a reason for the increase in soil pH as explained by prior research (Laghari et al., 2015; Griffin et al., 2017). As reported in this study, biochar added soils had elevated SOC contents in both 0-15 and 15-30 cm soil depth. This is applicable to a wide-range of experiments that reported SOC increases after biochar addition, improving soil quality in degraded soils (Brandão et al., 2011; Weng et al., 2017; Li et al., 2018). Corresponding findings by Jones et al. (2012) reported that biochar increases SOC contents after application at 25 t ha^{-1} and 50 t ha^{-1}. Also, it resonates with a report that biochar contributed to the organic C pool in the soil environment (Sohi, 2012; Simarani et al., 2018). Progressively, biochar addition relatively influenced the content of AN in-soil depth. This is in affirmation with prior studies that N concentration in soil was surged by the addition of biochar (Novak et al. 2010; Clough and Condron, 2010; Chintala et al., 2013). This result also tallies with Zhang et al. (2012) who reported that the inclusion of biochar at 20 and 40 t ha^{-1} accrued a significant increase in N concentration. Also, Haider et al. (2017), in a four-year field research observed biochar amendment increased soil mineral N at 0-15 cm soil depth while no impact was found at 15-30 cm depth. This simply implies that N retention in the soil may be related to the large surface area and high porosity of biochar providing adsorption sites (Singh et al., 2010; Bruun et al., 2012; Bhattacharjya et al., 2016). Biochar addition significantly contributed to increase in AP at both 0-15 and 15-30 cm soil depths. This aligns with a report by Farrell et al. (2014) who reported an increase in P concentration after biochar application. Besides that, Mahmoud et al. (2017) also found that P in soils increased when biochar was applied as soil amendments in degraded soil. In essence, P appears more available in soils to which biochar has been applied, both by acting as a source and by reducing losses of P and other cations from the system (Lehmann et al., 2011; Cui et al., 2011; Ameloot et al., 2013; Mukherjee and Lal, 2013). The available K (AK) was relatively modified by applied biochar in 0-15 and 15-30 cm soil depths. This coincides with that of El-Naggar et al. (2015) who reported biochar treatment had a positive influence on soil available K in the 0-30 cm soil depth. Also, Major et al. (2010) and Khorram et al. (2019) reported biochar increased available K in a long-term field study. This implies that considerable amount of K in biochar promoted changes in soil AK in this study. Prior studies have established that biochar amendment showed enhanced or no effects on soil K availability which might be due to use of different feedstock (Steiner et al., 2007; Gaskin et al., 2010; Lentz and Ippolito, 2012).

Soil microbial biomass

Biochar application could alter changes in soil microbial biomass pools (Teutscherova et al., 2017). Soil MBC increased with increasing biochar dose at 0-15 and 15-30 cm depth in both years. This is congruent with earlier reports that biochar application increased MBC at 0–30 cm soil depths (Paz-Ferreiro et al., 2012; Masto et al., 2013; Gomez et al., 2014; Noyce et al., 2015). The addition of biochar to soils has been suggested to provide more suitable environment for microbial activities and carbon mineralization (Liang et al., 2010; Lehmann et al., 2011; Dempster et al., 2012; Sun et al., 2015). The increased content of MBN at 0-15 and 15-30 cm depths in this study suggests high N turnover rate from organic N mineralization after biochar addition (Oladele et al., 2019). More so, biochar presence in soil accelerates microbial activities (Steiner et al., 2004; Kolb et al., 2009; Kuzyakov et al., 2009; Jones et al., 2012; Tang et al., 2013) which retains N through microbial cycling (Steiner et al., 2008). MBP has been considered as an important contributor of P in the soil (Redel et al., 2008). Biochar treatments increased MBP at both soil depths. Li et al. (2007) reported that addition of biochar increased MBP in a field experiment which implies biochar attributes to retaining P. Also, with the addition of biochar, increased MBP was mainly due to high P concentrations in the biochar and which provided P for the utilization of microbes (Zhai et al., 2015).

Conclusion

The 2 years field study showed that biochar application improved SOC, soil pH, available nutrients, and microbial biomass pools of Chernozemic soils. Higher biochar doses generally made way for greater effects across all measured parameters in both the upper and lower soil depths. The remarkable changes in soil carbon contents thus affirms biochar ability to increase soil carbon. Soil available nutrients remain positively influenced by biochar indicating that biochar can alter chemical properties of amended soil. The observed increases in microbial biomass pools coincides with the available soil nutrients generated from the use of biochar. This study indicates that biochar application is a credible practice for improving soil quality and enhancing microbial activities in studied soil. However, further research trials to elucidate the impact of other types biochar and its doses on Chernozemic soils is needed.

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Effects of poultry manure and graded nitrogen fertilizer doses on wheat yield, plant and soil nutrient contents, and soil electrical conductivity under greenhouse conditions

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Abstract

The integration of organic and inorganic fertilizers is gaining importance as a strategy to improve crop yield while maintaining soil health and reducing environmental risks. Poultry manure is a nutrient-rich organic amendment that can enhance soil fertility and partially replace synthetic nitrogen (N) fertilizers. This study aimed to evaluate the effects of poultry manure applied at six rates (0, 250, 500, 750, 1000, and 2000 kg/da) in combination with a fixed dose of chemical N fertilizer (20 kg N/da) on wheat (Triticum aestivum L.) yield, plant nutrient composition (N, P, K, Ca, Mg), soil nutrient availability, and soil electrical conductivity (EC) under greenhouse conditions. The experiment was conducted in 5 kg pots filled with clay loam soil (pH 7.6; $CaCO_3$ 9.6%; OM 1.35%). All pots received uniform basal applications of P and K (20 kg/da each). After 90 days, plants and soils were analyzed for nutrient contents. Results showed that grain yield significantly increased with manure application, reaching a peak of 5.74 kg/pot at 1000 kg/da. Grain N, K, and Ca contents increased significantly, while P and Mg showed minor or statistically non-significant trends. Soil nutrient levels also improved across all manure doses, particularly for N, K, and Ca. However, soil EC increased steadily from 1.39 to 3.12 dS/m with increasing manure dose, indicating a risk of salinity buildup at high application rates. The results suggest that poultry manure, when applied at moderate doses, can effectively improve wheat yield and nutrient availability while reducing the need for synthetic N fertilizers. However, EC monitoring is essential to avoid salinity-related constraints, especially in greenhouse or poorly drained conditions.

Keywords: Poultry manure, wheat yield, plant nutrient content, soil fertility, nitrogen substitution, electrical conductivity.

Introduction

Wheat (Triticum aestivum L.) is one of the most widely cultivated cereal crops globally, serving as a staple food and a major source of calories and protein for human populations (Shewry and Hey, 2015; Giraldo et al., 2019; Khalid et al., 2023; Nurgaliyeva et al., 2025). Improving wheat yield and nutritional quality while maintaining soil health is a critical challenge for sustainable agriculture (Al-Shammary et al., 2024). Among essential nutrients, nitrogen (N) plays a central role in determining plant growth, yield potential, and grain protein content (Agegnehu et al., 2016; Irfan et al., 2023). However, the intensive use of synthetic N fertilizers has led to several environmental and agronomic concerns, including nitrate leaching, soil

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acidification, greenhouse gas emissions, and declining nitrogen use efficiency (Guenzi et al., 1978; Eghball and Power, 1999).

In recent years, there has been growing interest in integrating organic amendments such as animal manures into nutrient management strategies (Upadhyay et al., 2022; Pajura, 2024; Omokaro et al., 2024). Poultry manure is a nutrient-dense organic material that supplies not only nitrogen but also phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and various micronutrients in forms readily mineralizable by soil microbes (Eghball et al., 2002; Du et al., 2020; Zhao et al., 2024). In addition to its fertilizing potential, poultry manure enhances soil structure, microbial activity, and water-holding capacity, thereby contributing to long-term soil fertility (Hati et al., 2006; Agbede, 2025). Nonetheless, the application of poultry manure at high rates may lead to the accumulation of soluble salts, resulting in increased soil electrical conductivity (EC), which can limit plant growth under conditions of restricted leaching, such as greenhouse or pot environments (Amin et al., 2022; Mahmoud et al., 2024).

Despite its known agronomic benefits, the potential of poultry manure to reduce the need for chemical nitrogen fertilizers—without compromising yield or nutrient status—remains a topic of ongoing research. Furthermore, its effect on soil nutrient dynamics and EC across a range of application doses requires systematic evaluation under controlled conditions. The objective of this study was to investigate the effects of increasing poultry manure doses (0–2000 kg/da), applied in combination with a uniform chemical nitrogen dose (20 kg N/da), on wheat grain yield, plant nutrient content (N, P, K, Ca, Mg), soil nutrient availability, and electrical conductivity in a greenhouse environment. Additionally, the study aimed to assess whether poultry manure can reduce reliance on synthetic nitrogen inputs by enhancing nutrient supply through organic means.

Material and Methods

Experimental Design and Setup

A greenhouse pot experiment was conducted to evaluate the effects of increasing doses of poultry manure (PM) on wheat (Triticum aestivum L.) yield, nutrient uptake, and soil chemical properties. The experiment followed a completely randomized design with six poultry manure doses: 0 (control), 250, 500, 750, 1000, and 2000 kg/da.

Each treatment was replicated three times, resulting in a total of 18 pots. Plastic pots were filled with 5 kg of clay-loam soil characterized by a pH of 7.6, 9.6% $CaCO_3$, 1.35% organic matter, and an initial electrical conductivity (EC) of 1.39 dS/m.

All pots received a basal application of 20 kg/da P_2O_5 (as triple superphosphate) and 20 kg/da K_2O (as potassium sulfate). Nitrogen was applied at a uniform rate of 20 kg N/da as ammonium nitrate in three equal splits: at sowing, tillering, and stem elongation stages.

Wheat seeds (15 per pot) were sown and grown under natural greenhouse conditions for 90 days. Pots were weighed daily, and water loss was replenished to maintain field capacity throughout the growing period.

Soil Properties and Fertilizer Application

The soil used in the experiment was classified as clay loam in texture, with a pH of 7.6, lime content ($CaCO_3$) of 9.6%, and organic matter content of 1.35%. Prior to the application of treatments, all pots received a basal dose of phosphorus and potassium fertilizers equivalent to 20 kg P_2O_5/da (as triple superphosphate, TSP) and 20 kg K_2O/da (as potassium sulfate, K_2SO_4), respectively. Nitrogen fertilizer was applied in three equal splits:

- 1/3 at sowing,
- 1/3 at the tillering stage,
- 1/3 at the stem elongation stage.

Animal waste materials were air-dried, ground, and incorporated into the soil at the respective rates one week before sowing.

Greenhouse Conditions and Water Management

Throughout the 90-day growth period, pots were maintained at field capacity by daily weighing and rewatering to compensate for evapotranspiration. Greenhouse temperatures ranged between 18–25°C with a 14-hour photoperiod.

Harvest and Sample Analysis

Plants were harvested 90 days after sowing and total grain yield per pot (kg) was recorded. At the end of the experiment soil and grain samples were collected from each pot. Soil samples were analyzed for total nitrogen by Kjeldahl method (Bremner, 1965), available phosphorus in a 0.5 M $NaHCO_3$ extract using a spectrophotometer (Olsen and Dean, 1965), and, exchangeable cations (K, Ca and Mg) were extracted with 1 N ammonium acetate; K and Na were determined by flame photometry, while Ca and Mg were measured by EDTA titration (Pratt, 1965; Heald, 1965).

The harvested grain materials were dried in an oven at 65°C until a constant weight was achieved. The dried samples were subsequently weighed using a precision balance to determine the grain yields per pot. For nutrient analysis, the dried grain samples were ground to a fine powder and analyzed for their N, P, K, Ca and Mg contents. The nitrogen content was determined using the Kjeldahl method, while phosphorus was analyzed using the molybdo-vanadate spectrophotometric method. Potassium content was measured with a flame photometer. The concentrations of Ca and Mg were determined by AAS following the methodology described by Jones (2001).

Statistical Analysis

All data were analyzed using one-way ANOVA to evaluate the effects of poultry manure doses on wheat yield, nutrient contents, and soil electrical conductivity. Treatment effects were assessed using F-values. Standard statistical procedures were applied, and treatment means were interpreted based on F-statistics.

Results and Discussion

Grain Yield Response

The grain yield of wheat was significantly affected by increasing poultry manure application doses (Table 1). In the control treatment (0 kg/da), the lowest mean grain yield was recorded as 4.85 ± 0.11 kg/pot. Yield increased progressively with the application of poultry manure, reaching 5.20 ± 0.02 kg/pot at 250 kg/da, and continued to increase up to 5.74 ± 0.03 kg/pot at 1000 kg/da. The highest dose, 2000 kg/da, resulted in a statistically similar yield (5.75 ± 0.08 kg/pot) to the 1000 kg/da treatment, indicating a yield plateau beyond this level. The one-way ANOVA test revealed that the differences in yield among treatments were highly significant ($P<0.001$). This indicates that poultry manure, particularly at moderate to high doses (750–1000 kg/da), effectively enhances wheat productivity under greenhouse conditions. The observed yield improvement is likely due to the enhanced availability of essential nutrients, improved soil physical structure, and increased microbial activity facilitated by the organic amendment.

These findings are consistent with previous studies by Eghball and Power (1999) and Savala et al. (2016), who reported that poultry manure increased wheat yield by supplying nitrogen and phosphorus in plant-available forms. Similarly, Agegnehu et al. (2016) and El-Ghamry et al. (2024) highlighted the synergistic effects of organic amendments on crop performance through both nutritional and non-nutritional mechanisms. However, the absence of further yield increase at 2000 kg/da may indicate either nutrient saturation or possible adverse effects such as salinity buildup or nutrient imbalances at excessively high application rates. This suggests that while poultry manure is a valuable nutrient source, its application should be optimized based on crop demand and soil buffering capacity. Furthermore, the application of poultry manure at 1000 kg/da, in combination with a modest chemical nitrogen dose of 20 kg N/da, resulted in grain yields statistically equivalent to those obtained at higher manure doses. This indicates that poultry manure can effectively enhance nitrogen availability and meet crop demand without the need for additional synthetic nitrogen inputs. Such results support the potential for partial substitution of chemical N fertilizers with organic sources, contributing to more sustainable and integrated nutrient management strategies.

Table 1. Effect of poultry manure dose on wheat grain yield (kg/pot), ***P<0,001; **P<0,01, *P<0,05, ^{ns} not-significant

Poultry Manure Dose (kg/da)	Value (Mean ± SD)
0	4.85 ±0.11
250	5.20 ±0.02
500	5.40 ±0.13
750	5.64 ±0.06
1000	5.74 ±0.03
2000	5.75 ±0.08
F value	65.50 ***

Plant Nutrient Content

The concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) in wheat grain responded differently to poultry manure application (Table 2). While most nutrients showed a significant increase with increasing manure doses, phosphorus and magnesium remained statistically unaffected. The differences among treatments are discussed in detail below.

Grain nitrogen concentration increased significantly with poultry manure doses, from 1.25 ± 0.04% in the control to 2.03 ± 0.04% at the highest application rate of 2000 kg/da. The increase was statistically significant (P<0.001). The improvement in grain N content can be attributed to the high organic N content of poultry manure and its rapid mineralization, which increases ammonium and nitrate availability in the root zone. Nitrogen is a key determinant of grain protein content, and its improved availability often directly enhances N accumulation in grain (Agegnehu et al., 2016).

Phosphorus content ranged from 0.26 ± 0.06% to 0.37 ± 0.01%, but the differences were not statistically significant. Despite poultry manure being rich in phosphorus, it is possible that the applied P exceeded plant uptake capacity or was immobilized due to soil pH and calcium carbonate interactions. These findings align with Bhat et al (2017) and Wu et al. (2020), who noted that organic P availability is highly influenced by soil characteristics and microbial activity.

Potassium concentration showed a clear and statistically significant increase, from 1.60 ± 0.06% (control) to 2.06 ± 0.01% at 2000 kg/da (P<0.001). Poultry manure is a known source of readily available potassium, which plays a vital role in osmoregulation, photosynthate transport, and grain filling. The results corroborate the work of Eghball et al. (2002), who observed that manure-derived K is highly effective in enhancing K uptake and accumulation in cereal grains.

Grain calcium levels increased from 0.35 ± 0.06% (control) to 0.50 ± 0.03% at the highest manure dose, with a statistically significant variation among treatments (P<0.05). Though not a primary macronutrient for yield, Ca supports structural development of cell walls and physiological resilience. Poultry manure contains moderate amounts of Ca, and its repeated use can enrich soil Ca pools, as observed in this study.

Magnesium content showed a positive but statistically non-significant trend. Values ranged from 0.18 ± 0.05% to 0.28 ± 0.03% across treatments. Mg plays a crucial role in chlorophyll synthesis and enzyme activation. Although the increasing trend is agronomically relevant, variability among replicates may have masked the statistical significance.

Overall, poultry manure significantly enhanced N, K, and Ca concentrations in wheat grain, while P and Mg responses were moderate or statistically insignificant. These findings underline the effectiveness of poultry manure in improving plant nutritional status, particularly for nitrogen and potassium.

Table 2. Effect of poultry manure dose on grain nutrient content (% dry matter)

Poultry Manure Dose (kg/da)	Plant N (%)	Plant P (%)	Plant K (%)	Plant Ca (%)	Plant Mg (%)
0	1.25 ±0.04	0.26 ±0.06	1.60 ±0.06	0.35 ±0.06	0.18 ±0.05
250	1.47 ±0.06	0.33 ±0.03	1.71 ±0.05	0.38 ±0.05	0.21 ±0.05
500	1.59 ±0.06	0.31 ±0.02	1.83 ±0.06	0.40 ±0.04	0.23 ±0.04
750	1.77 ±0.04	0.32 ±0.02	1.94 ±0.04	0.44 ±0.03	0.25 ±0.04
1000	1.90 ±0.03	0.35 ±0.01	2.04 ±0.02	0.47 ±0.03	0.27 ±0.03
2000	2.03 ±0.04	0.37 ±0.01	2.06 ±0.01	0.50 ±0.03	0.28 ±0.03
F value	28.19***	1.72^{ns}	30.91***	3.81*	2.94^{ns}

***P<0,001; **P<0,01, *P<0,05, ^{ns} not-significant

Soil Nutrient Content

Post-harvest soil nutrient analysis revealed that increasing doses of poultry manure significantly improved the concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) in the soil (Table 3). These enhancements are attributable to the high nutrient content of poultry manure and its ability to release nutrients gradually through mineralization.

Soil N content increased markedly from 40.00 ± 0.05 mg/kg in the control to 70.01 ± 0.06 mg/kg at the 2000 kg/da poultry manure dose. The effect was statistically highly significant (P<0.001). This increase reflects the rapid decomposition and mineralization of organic nitrogen in poultry manure, which enhances the soil's nitrate and ammonium pool. These findings are in line with those of Guenzi et al. (1978), who reported sustained increases in soil N following organic manure applications.

Soil available phosphorus increased steadily with manure dose, ranging from 11.97 ± 0.04 mg/kg in the control to 22.04 ± 0.10 mg/kg at the highest dose (P<0.001). Poultry manure is rich in orthophosphates that are directly available to plants and contribute to the labile P pool in the soil. However, P availability may still be influenced by soil pH, calcium carbonate, and Fe/Al oxides. The observed increase supports the results of Eghball and Power (1999), who found manure-derived phosphorus to be effective in both short- and long-term soil P enhancement.

Soil exchangeable potassium rose from 220.02 ± 0.05 mg/kg to 345.00 ± 0.07 mg/kg across the poultry manure gradient, with the effect being highly significant (P<0.001). This increase is attributed to the high K content of poultry manure and its rapid solubility in the soil solution. Potassium is less prone to immobilization, making it readily available to plants and detectable in soil analysis soon after application.

Calcium content increased from 1849.97 ± 0.04 mg/kg (control) to 2150.01 ± 0.06 mg/kg in the highest manure treatment (P<0.001). Although not always measured in routine fertilization studies, calcium from poultry manure (derived from feed and bedding) contributes to the base saturation and structural stability of soils. These results align with the findings of Hati et al. (2006), who emphasized the long-term soil conditioning effect of manure-derived Ca.

Soil Mg content followed a similar increasing trend, rising from 209.99 ± 0.08 mg/kg to 260.01 ± 0.04 mg/kg, with statistically significant variation (P<0.001). As an essential secondary nutrient, Mg improves cation exchange capacity and supports chlorophyll biosynthesis in crops. Repeated poultry manure applications appear to replenish soil Mg stocks effectively.

Overall, poultry manure application improved the overall nutrient status of the soil, offering both immediate nutrient supply and residual fertility benefits. These improvements are crucial for sustaining crop productivity and reducing dependency on mineral fertilizers over time.

Table 3. Effect of poultry manure dose on soil nutrient content (mg/kg)

Poultry Manure Dose (kg/da)	Soil N	Soil P	Soil K	Soil Ca	Soil Mg
0	40.00 ±0.05	11.97 ±0.04	220.02 ±0.05	1849.97 ±0.04	209.99 ±0.08
250	45.97 ±0.02	14.02 ±0.02	245.02 ±0.04	1909.98 ±0.05	219.98 ±0.05
500	52.04 ±0.05	15.97 ±0.05	270.03 ±0.03	1970.03 ±0.04	230.03 ±0.03
750	57.99 ±0.02	17.95 ±0.05	294.98 ±0.03	2029.98 ±0.08	239.96 ±0.01
1000	64.01 ±0.05	19.99 ±0.12	319.96 ±0.08	2090.01 ±0.02	250.05 ±0.03
2000	70.01 ±0.06	22.04 ±0.10	345.00 ±0.07	2150.01 ±0.06	260.01 ±0.04
F value	119.82***	98.42***	153.51***	167.64***	121.70***

***P<0,001; **P<0,01, *P<0,05, ^{ns} not-significant

Soil Electrical Conductivity

Soil electrical conductivity (EC), an indicator of soluble salt concentration, increased steadily with the application of poultry manure (Table 4). The initial EC value in the control treatment (0 kg/da) was 1.39 ± 0.03 dS/m, which rose to 1.75 ± 0.02 dS/m at 250 kg/da and reached 3.12 ± 0.03 dS/m at the highest application rate of 2000 kg/da. The differences among treatments were statistically highly significant (P<0.001).

This trend is expected, as poultry manure contains substantial amounts of soluble nutrients such as ammonium, potassium, nitrate, and organic salts, all of which contribute to increased ionic strength in the soil solution. The linear increase in EC across manure doses suggests that these soluble compounds are not only released rapidly but also accumulate progressively under limited leaching conditions typical of pot or greenhouse experiments.

While EC levels up to 2.5–3.0 dS/m are generally considered tolerable for most wheat cultivars (Maas and Hoffman, 1977), prolonged exposure to elevated EC values—especially in soils with poor drainage or under arid conditions—can pose a risk of salinity stress. High EC interferes with water uptake by plants, leading to osmotic stress, reduced nutrient absorption, and ultimately yield decline if not properly managed.

The plateau in grain yield beyond the 1000 kg/da dose observed in this study may, in part, be attributed to the increasing EC values approaching critical thresholds. Therefore, although poultry manure is a valuable organic fertilizer, application rates must be optimized not only based on nutrient supply but also taking into account potential salinity buildup.

These findings are supported by earlier studies, including Santos et al (2018) and Adeyemo et al. (2019), who reported significant EC increases in soils amended with poultry manure, particularly under restricted leaching. Similarly, Du et al. (2020) and Zhao et al. (2024) emphasized the need for integrated nutrient and salinity management when using organic amendments at high rates.

These findings indicate that poultry manure increases soil EC in a dose-dependent manner, reflecting its nutrient richness but also highlighting the importance of dose regulation. Under field conditions with adequate leaching, the salinity risk may be lower, but in pot or greenhouse environments, monitoring EC is essential to prevent negative impacts on crop health.

Table 4. Effect of poultry manure dose on soil electrical conductivity (dS/m)

Poultry Manure Dose (kg/da)	EC (dS/m)
0	1.39 ±0.03
250	1.75 ±0.02
500	2.10 ±0.04
750	2.45 ±0.03
1000	2.80 ±0.03
2000	3.12 ±0.03
F value	117.55***

***P<0,001; **P<0,01, *P<0,05, ^{ns} not-significant

Conclusion

This greenhouse study demonstrated that poultry manure significantly improves wheat grain yield, enhances plant nutrient uptake, and enriches soil fertility. The application of poultry manure at increasing doses (0–2000 kg/da) resulted in marked improvements in grain yield, particularly up to the 1000 kg/da level, beyond which yield gains plateaued.

Grain nutrient concentrations, especially nitrogen and potassium, responded positively and significantly to manure application, confirming the effectiveness of poultry manure as a source of readily available macronutrients. Soil analyses further revealed consistent increases in available nitrogen, phosphorus, potassium, calcium, and magnesium, indicating strong residual effects of poultry manure that can benefit subsequent crops.

However, a concurrent rise in soil electrical conductivity was observed, reaching 3.12 dS/m at the highest application dose. While still within wheat's tolerance range, this suggests a potential risk of salinity accumulation, particularly under greenhouse or pot conditions where leaching is limited. Thus, manure application rates should be optimized to maximize yield and nutrient availability while minimizing salinity-related constraints.

Overall, the results suggest that poultry manure, when applied at appropriate doses (e.g., 750–1000 kg/da), can partially substitute for chemical fertilizers by improving both soil fertility and crop performance. Nevertheless, long-term field studies are recommended to evaluate cumulative effects on soil properties and crop rotation systems, and assess poultry manure's contribution to nutrient cycling, residual effects, and soil microbial balance over multiple growing seasons.

In particular, the study demonstrates that poultry manure, when applied at a dose of 1000 kg/da along with a moderate level of chemical nitrogen (20 kg N/da), can produce optimal wheat yields. This suggests that poultry manure has the potential to reduce dependency on synthetic nitrogen fertilizers, making it a viable component in integrated nutrient management systems. Future field-scale research should further investigate the degree to which organic amendments can replace chemical N inputs without compromising productivity.

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