2024

Volume : 13
Issue : 4
Page : 284 - 375

e-ISSN : 2147-4249

Eurasian Journal of Soil Science

Editor(s)-in-chief
Dr.Rıdvan KIZILKAYA
Dr.Evgeny SHEIN
Dr.Coskun GULSER

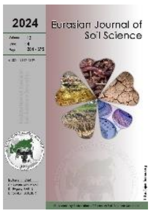
http://ejss.fesss.org

Published by Federation of Eurasian Soil Science Societies

EURASIAN JOURNAL OF SOIL SCIENCE

(Peer Reviewed Open Access Journal)

Published by Federation of Eurasian Soil Science Societies



EDITORS-IN-CHIEF

Dr.Rıdvan KIZILKAYA
Ondokuz Mayıs University, Türkiye

Dr.Evgeny SHEIN
Moscow State University, Russia

Dr.Coşkun GÜLSER
Ondokuz Mayıs University, Türkiye

EDITORIAL BOARD

Dr.Amrakh I. MAMEDOV, Azerbaijan
Dr.Brijesh Kumar YADAV, India
Dr.Carla FERREIRA, Sweden
Dr.Guilhem BOURRIE, France
Dr.Guy J. LEVY, Israel
Dr.Gyozo JORDAN, Hungary
Dr.Haruyuki FUJIMAKI, Japan
Dr.Hayriye IBRIKCI, Türkiye
Dr.İbrahim ORTAŞ, Türkiye
Dr.Jae YANG, South Korea
Dr.Jun YAO, China
Dr.Mohammad A. HAJABBASI, Iran
Dr.Nicolai S. PANIKOV, USA
Dr.Shamshuddin JUSOP, Malaysia
Dr.Sokrat SINAJ, Switzerland
Dr.Tatiana MINKINA, Russia
Dr.Vít PENIZEK, Czech Republic
Dr.Yakov PACHEPSKY, USA
Dr.Yury N. VODYANITSKII, Russia

DIVISION EDITORS

Dr.Aminat UMAROVA, Soil Physics and Mechanic, Russia
Dr.David PINSKY, Soil Chemistry, Russia
Dr.Hassan EL-RAMADY, Soil Fertility, Egypt
Dr.İmanverdi EKBERLİ, Applied Mathematic in Soil Science, Türkiye
Dr.Kadir SALTALI, Soil Degradation and Reclamation, Türkiye
Dr.Metin TURAN, Plant Nutrition, Türkiye
Dr.Mustafa BOLCA, Soil Survey and Mapping, Türkiye
Dr.Nikolay KHITROV, Soil Genesis and Classification, Russia
Dr.Orhan DENGİZ, Remote Sensing and GIS in Soil Science, Türkiye
Dr.Sait GEZGİN, Fertilizer and Fertilization, Türkiye
Dr.Sezai DELİBACAK, Soil Health and Quality, Türkiye
Dr.Svatopluk MATULA, Soil Hydrology, Czech Republic
Dr.Svetlana SUSHKOVA, Soil Pollution, Russia
Dr.Taşkın ÖZTAŞ, Soil Erosion and Conservation, Türkiye
Dr.Tayfun AŞKIN, Geostatistics, Türkiye
Dr.Tomasz ZALESKI, Soil Mineralogy & Micromorphology, Poland
Dr.Victor B. ASIO, Soil Management, Philippines
Dr.Vishnu D. RAJPUT, Soil Biology and Biochemistry, Russia

SCIENTIFIC EDITORS

Dr.Alexander MAKEEV, Russia
Dr.Benyamin KHOSHNEVİSAN, China
Dr.Fariz MIKAILSOY, Türkiye
Dr.Füsun GÜLSER, Türkiye
Dr.Galina STULINA, Uzbekistan
Dr.H. Hüsnü KAYIKÇIOĞLU, Türkiye
Dr.İzzet AKÇA, Türkiye
Dr.János KÁTAI, Hungary
Dr.Lia MATCHAVARIANI, Georgia
Dr.Marketa MIHALIKOVA, Czech Republic
Dr.Maja MANOJLOVIC, Serbia
Dr.Niyaz Mohammad MAHMOODI, Iran
Dr.Ramazan ÇAKMAKCI, Türkiye
Dr.Ritu SINGH, India
Dr.Saglara MANDZHIEVA, Russia
Dr.Saoussen HAMMAMI, Tunusia
Dr.Srdjan ŠEREMEŠİĆ, Serbia
Dr.Velibor SPALEVIC, Montenegro

ADVISORY EDITORIAL BOARD

Dr.Ajit VARMA, India
Dr.David MULLA, USA
Dr.Donald GABRIELS, Belgium
Dr.İsmail ÇAKMAK, Türkiye
Dr.Nicola SENESI, Italy

HONORARY BOARD

Dr.Ayten NAMLI, Türkiye
Dr.Beibut SULEIMENOV, Kazakhstan
Dr.Ermek BAIBAGYSHOV, Kyrgyzstan
Dr.Garib MAMMADOV, Azerbaijan
Dr.Hamid ČUSTOVIĆ, Bosnia & Herzegovina
Dr.Irina Carmen CALCIU, Romania
Dr.Mihajlo MARKOVİĆ, Serbia
Dr.Pavel KRASILNIKOV, Russia

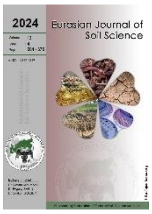
LINGUISTIC EDITOR

Birol KURT, Türkiye
Gregory T. SULLIVAN, Australia
Oksana FOTINA, Russia
Yelena KANDALINA, Kazakhstan

ABOUT THIS JOURNAL: Eurasian Journal of Soil Science is the official English language journal of the Federation of Eurasian Soil Science Societies. Eurasian Journal of Soil Science peer-reviewed open access journal that publishes research articles, critical reviews of basic and applied soil science in all related to soil and plant studies and general environmental soil science.

ABSTRACTING AND INDEXING: SCOPUS, CABI, FAO-Agris, EBSCOhost, ProQuest, DOAJ, OAJI, TR Dizin, TURKISH Journalpark, CrossRef, CiteFactor, CAS, etc.

Year: 2024, Volume: 13, Issue: 4, Page: 284 - 375 **e-ISSN 2147-4249**



EURASIAN JOURNAL OF SOIL SCIENCE

(Peer Reviewed Open Access Journal)

Published by Federation of Eurasian Soil Science Societies

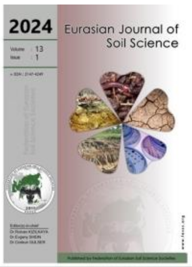
YEAR: 2024 **VOLUME : 13** **ISSUE : 4** **PAGE : 284 - 375**

CONTENTS

Eurasian Journal of Soil Science 2024, 13(4), 284 - 293

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



Effect of zeolite application on soil enzyme activity of potted sandy soil cultivated with Swiss chard and cabbage

Olwetu Antonia Sindesi [a,*], Muinat Nike Lewu [b], Bongani Ncube [c], André Meyer [b], Azwimbavhi Reckson Mulidzi [b], Francis Bayo Lewu [a]

[a] Department of Agriculture, Faculty of Applied Sciences, Cape Peninsula University of Technology, Private Bag X8, Wellington 7654, South Africa

[b] Soil and Water Science Programme, Agricultural Research Council Infruitec-Nietvoorbij, Private Bag X5026, Stellenbosch 7599, South Africa

[c] Centre for Water and Sanitation Research, Faculty of Engineering & the Built Environment, Cape Peninsula University of Technology, Bellville 7535, Cape Town, South Africa

Article Info

Received : 07.12.2023
Accepted : 03.06.2024
Available online: 06.06.2024

Author(s)

O.A.Sindesi *
M.N.Lewu
B.Ncube
A.Meyer
A.R.Mulidzi
F.B.Lewu

* Corresponding author

Abstract

A zeolite pot experiment was conducted at the Agricultural Research Council Infruitec-Nietvoorbij in Stellenbosch, South Africa, under greenhouse conditions. The experiment aimed to investigate the impact of zeolite application on soil enzyme activities in sandy soils cultivated with Swiss chard (*Beta vulgaris* Var. *cicla*) and cabbage (*Brassica oleracea* Var. *capitata* L.) over two years (2018-2019). Different zeolite-to-soil ratios (0:1, 1:9, 2:8, and 3:7 w/w) were used, with each pot containing 12 kg of soil. The experiment involved 72 pots for each vegetable, arranged in a randomized complete block design (RCBD). Soil enzyme activities, including acid phosphatase, β-glucosidase, and urease, as well as soil chemical properties (pH, total plant-available nitrogen, organic carbon, and phosphorus), were analyzed. Key findings indicate that the effect of zeolite application on enzyme activities varied between the vegetable species. Zeolite application significantly increased ($P<0.05$) soil pH across all treatments. However, higher zeolite levels decreased ($P<0.05$) soil phosphorus availability, likely due to phosphorus adsorption by zeolite. Acid phosphatase activity decreased with rising zeolite levels, possibly due to increased soil pH. Additionally, zeolite application reduced ($P<0.05$) soil organic carbon, which may explain some of the enzyme activity responses. Alteration Index Three (AI3) scores suggested improved soil biological activity with zeolite application, although responses varied between crops. Cabbage soils showed improvement in all treatments, while Swiss chard soils exhibited mixed responses. In conclusion, while zeolite application can enhance soil pH and nutrient retention, it may also reduce phosphorus availability and organic carbon. The enzyme activity responses observed are complex and crop-specific, highlighting the need for tailored soil management practices. Further research is recommended to explore the long-term impacts and optimal integration of zeolite with organic amendments for sustainable soil fertility management.

Keywords: Zeolite, organic carbon content, soil amendment, urease, phosphates, β-glucosidase.

Introduction

In African countries, soil fertility has generally declined due to the intensification of agriculture aimed at feeding the growing population (Tully et al., 2015). The decline in soil fertility can be addressed through the use of organic amendments such as farmyard manure, compost, and plant residues, and more commonly, through inorganic fertilizers (Munir et al., 2012; Celestina et al., 2019; Albano et al., 2023). Inorganic fertiliser

doi : https://doi.org/10.18393/ejss.1496891
: https://ejss.fesss.org/10.18393/ejss.1496891
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

application requires significant financial contributions, and over-application results in environmental degradation (Kakar et al., 2020). On the one hand, organic amendments are unstable in soil and decompose over time (Fujino et al., 2008). Therefore, more suitable stable amendments such as zeolite are needed to reduce soil fertility decline. Zeolites are inorganic materials found naturally; they are aluminosilicate minerals with porous structures with high cation exchange capacity (CEC) and affinity toward ammonium (NH_4^+) and potassium (K^+) cations (Pabalan and Bertetti, 2001; Sindesi et al., 2023a).

Zeolite has been found to improve soil pH, water-holding capacity, and nutrient retention (de Campos Bernardi et al., 2013; Nur Aainaa et al., 2018; Sindesi et al., 2023b). These improvements are attributed to the properties of zeolite (porous nature and high CEC). Zeolite improves the growth of plants cultivated in soils amended with zeolite (Ramesh et al., 2015) through improved soil chemical and physical properties (Nur Aainaa et al., 2018). However, there are limited studies on the impact of zeolite application on soil biological activities, including enzyme activity. Soil enzyme activity is one of the key soil fertility parameters as enzymes assist in mineralizing organic nutrients, thereby making them available for plants and soil microorganisms (Al et al., 2015). Enzymes indicate soil quality, as many soil enzymes respond almost immediately to changes in soil fertility status (Tejada et al., 2008; Guangming et al., 2017). According to Kaurin et al. (2018), soil texture, pH, and nutrient availability contribute to soil enzyme and microbial activities.

Soil enzyme activities are sensitive to environmental and soil changes (Alkorta et al., 2003). Some of the most sensitive enzymes are urease, phosphates and β-glucosidase (Guangming et al., 2017; Asadishad et al., 2018). These are responsible for promoting the hydrolysis of nitrogen (N) containing organic matter, the cycling of phosphorus (P), and the hydrolysis of glycosides, which play a crucial role in soil carbon (C) cycling, respectively (Guangming et al., 2017; Asadishad et al., 2018; Kaurin et al., 2018). The activity of soil enzymes has been used in soil health research (Alkorta et al., 2003; Meena and Rao, 2021; Kanté et al., 2021). This study assessed the effect of zeolite application on the activity of soil urease, phosphates, and β-glucosidase of potted sandy soil cultivated with Swiss chard and cabbage over two growing seasons.

Material and Methods

Experimental site and treatment details

A greenhouse pot experiment was conducted at the Agricultural Research Council Infruitec-Nietvoorbij in Stellenbosch, South Africa, to assess the impact of zeolite on soil microbial enzyme activity over two growing seasons (2018 and 2019). The first season was late autumn to late spring 2018 and the second season was early autumn to early spring 2019. Two vegetables were used cabbage cv. Copenhagen (*Brassica oleracea* Var. *capitata* L.) and Swiss chard cv. Ford Hook Giant (*Beta vulgaris* Var. *cicla*). Zeolite was applied to sandy soil at the ratios 0:1, 1:9, 2:8, and 3:7 *(w/w)* in 12 kg pots with a diameter of 30 cm. The experiment used 144 pots, 72 pots for Swiss chard, and 72 pots for cabbage. The pots were arranged in a randomized complete block design (RCBD). In each season, Swiss chard was grown for 133 days, while cabbage was grown for 126 days. For basal fertilization, 1.17 g pot^{-1} and 3 g pot^{-1} urea (46% N) and single-super phosphate (20% P_2O_5) were applied, respectively, on both crops. Basal potassium chloride (50% K_2O) was applied at 1.92 g pot^{-1} for cabbage and 1.44 g pot^{-1} for Swiss chard. At 4 and 8 weeks after transplanting, 0.33 g pot^{-1} urea was used as a side dress fertilizer for Swiss chard. On cabbage 1.11 g pot^{-1} urea was applied in split applications at 3 and 6 weeks after transplanting. Throughout the experiment, soil moisture was analysed using the gravimetric method and was kept between 50 and 75% of pot capacity. Insect pests were controlled using Makhro Cyper® (active ingredient: cypermethrin, 200 g L^{-1}) in the first growing season (2018). Avi Gard Mercaptothion® (active ingredient Organophosphate 500 g L^{-1}) was used in the second growing season.

Data collection

Before applying zeolite, a composite soil sample was taken to analyse soil enzyme activity and related soil chemistry. On the day of harvest, soil samples were taken for the assessment of treatment effects. The soil enzymes analyzed were β-glucosidase, acid phosphatase, and urease, using methods of Eivazi and Tabatabai (1988), Icoz and Stotzky (2008), and (Kandeler and Gerber, 1988), respectively. The enzyme activity data were then converted to Alteration Index Three (AI3) scores using the methods described in the work of Huyssteen et al. (2020).

The substrates used for the analysis of the enzymes β-glucosidase, acid phosphatase, and urease were 4-MUB-β-D-glucoside, 4-MUB-phosphate, and a urea solution, respectively. Available P was analysed using the ICP-OES Bray II method (Non-affiliated Soil Analysis Work Committee, 1990), and plant available nitrogen (NH_4-N and NO_3-N) was analysed using the sodium tetraphenylborate method (Howa et al., 2014). The two plant-available nitrogen types were added together to obtain the total plant-available nitrogen. Soil organic carbon content was measured using the Walkley-Black method (Walkley and Black, 1934), while soil pH was analyzed using the Potassium Chloride (KCl) method (Okalebo et al., 2022).

Data analysis

Data were analysed using SAS (version 9.4, SAS Institute Inc., Cary, NC, USA, 2000) software for Analysis of Variance (ANOVA) to compare treatment means. After determining whether there was seasonal homogeneity of variance using Levene's test, the results from both seasons were merged and assessed using a single overall ANOVA. The Shapiro-Wilk test was employed to check for outliers and non-significant interactions. Fisher's least significant difference was calculated at the 5% level to compare treatment means. A significance level of 5% was regarded as appropriate for all tests. Pearson correlation coefficients *(r)*, correlating the soil chemical parameters and soil enzyme activities, were derived using the CORR procedure of SAS 9.4.

Results and Discussion

Baseline soil parameters

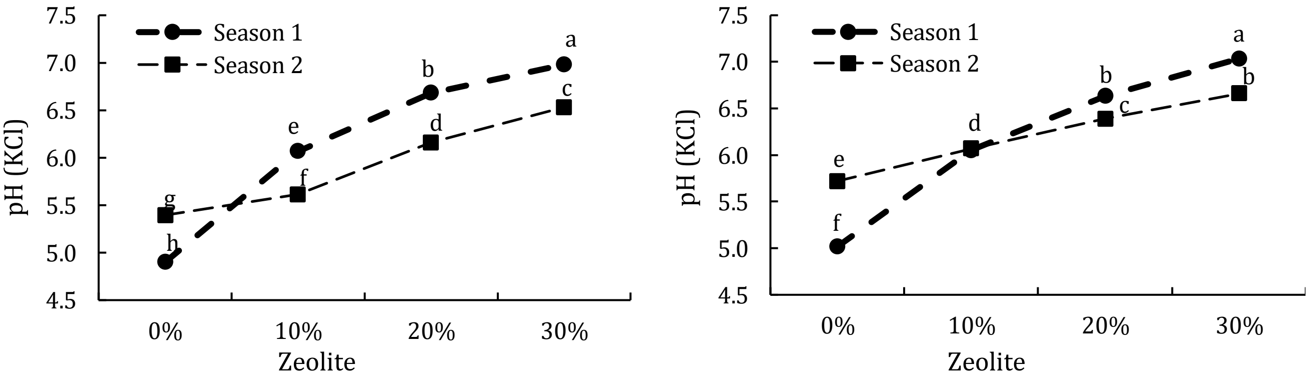
Table 1 shows the baseline soil parameters of the soil used for the experiments: The soil chemical status was conducive for cabbage and Swiss chard growth.

Table 1. Soil baseline chemistry and enzyme activity

Chemical analysis	Value
pH (KCl)	5.40
Organic C (%)	0.89
Available P (mg kg^{-1})	47.00
NO_3-N (mg kg^{-1})	32.76
NH_4-N (mg kg^{-1})	7.11
Enzyme Activity	Activity
Acid phosphatase (p-nitrophenol µg/g/h)	137.93
β-glucosidase (p-nitrophenol µg/g/h)	9.17
Urease (NH_4-N µg/g/2h)	9.80

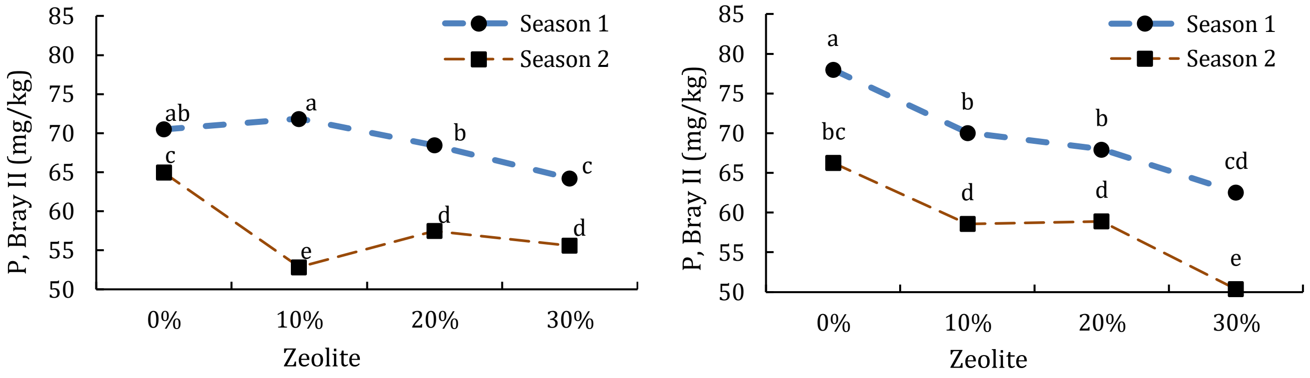
Soil pH and phosphatase activity responses to the application of zeolite on cabbage and Swiss chard potted sandy soils

Soil pH is one of the leading factors that influence soil microbial composition and enzyme activity (Ai et al., 2015). In this study, zeolite application increased soil pH (Figure 1) due to the alkaline nature, high CEC, and the negative charges of zeolite as explained in the earlier work of Sindesi et al. (2021). The availability of P (Figure 2) also generally decreased with the increase in zeolite application. The phosphorus applied to the soil was in the form of phosphorus pentoxide (P_2O_5), which is plant-available/water-soluble. When P_2O_5 encounters zeolite, it undergoes an adsorption process and diffuses into the particles of zeolite, which decreases its availability in the soil (Onyango et al., 2007).



(a) (b)

Figure 1. Soil pH responses to zeolite application (a) cabbage and (b) Swiss chard at the end of each season. Bars with the same letter are not significantly different



(a) (b)

Figure 2. Responses of soil P to zeolite application (a) cabbage and (b) Swiss chard at the end of each season. Bars with the same letter are not significantly different

Phosphate cycling is facilitated by phosphatase enzymes, specifically acid and alkaline phosphomonoesterases; these have been extensively studied (Nannipieri et al., 2011). In this study, acid phosphatase was studied. The optimal pH range for the activity of acid phosphatase is between the pH range of 4.0 and 5.5 (Mazorra et al., 2002). The soil pH of all the zeolite-amended soils was above 5.5 (Figure 1), and the activity of phosphatase decreased with the increased application of zeolite (Figure 3). Additionally, soil pH negatively correlated with the activity of acid phosphatase for both cabbage and Swiss chard potted soils (Table 2 and 3). This was in line with the observations made by Dick et al. (1988). This negative correlation with pH was also observed by Margalef et al. (2017).

Table 2. Pearsons's correlation coefficients *(r)* between soil enzyme activity and soil nutrients from cabbage potted zeolite amended soils (Seasons 1 and 2 combined)

Variables	Pearsons's correlation coefficients *(r)*			
	A	B	C	D
Soil C	-0.495***	-0.142	-0.201	-0.659***
NO_3-N	-0.778***	-0.511***	-0.208	-0.717***
NH_4-N	-0.375**	-0.296*	-0.187	-0.210
Total N (NO_3 + NH_4)	-0.754***	-0.525***	-0.254	-0.613***
P Bray II	-0.702***	-0.349**	-0.236	-0.731***
pH (KCL)	-0.245	-0.474***	-0.063	0.136

^{A} β-Glucosidase, ^{B} Acid Phosphatase, ^{C} Urease, ^{D} Alteration index 3. * Correlation is significant at 0.05 level, **Correlation is significant at 0.01 level, **Correlation is significant at 0.001 level

Table 3. Pearsons's correlation coefficients *(r)* between soil enzyme activity and soil nutrients from Swiss chard potted zeolite amended soils (Seasons 1 and 2 combined)

Variables	Pearsons's correlation coefficients *(r)*			
	A	B	C	D
Soil C	-0.045	-0.222	-0.481***	-0.201
NO_3-N	0.133	0.606***	-0.201	0.336**
NH_4-N	-0.26	-0.361**	-0.403**	-0.202
Total N (NO_3 + NH_4)	-0.082	0.162	-0.393**	0.089
P Bray II	0.122	-0.263	-0.495***	-0.195
pH (KCL)	-0.569***	-0.321**	0.381**	-0.136

^{A} β-Glucosidase, ^{B} Acid Phosphatase, ^{C} Urease, ^{D} Alteration index 3. * Correlation is significant at 0.05 level, **Correlation is significant at 0.01 level, **Correlation is significant at 0.001 level

The correlation results also show that acid phosphatase activity negatively correlated with the availability of soil P in cabbage-potted soils, while Swiss chard-potted soils showed a weak negative correlation (Table 2 and 3). This may be attributed to a reduction in soil organic matter and the application of inorganic P; the former is observed through the reduction of soil organic C content (Figure 4) with increased zeolite application. There was also a non-significant weak negative correlation between acid phosphatase and soil organic content. The reduction in soil organic matter reduces the phosphomonoester metabolites, which phosphatases work on to release inorganic phosphate from the substrates (Dick et al., 2011).

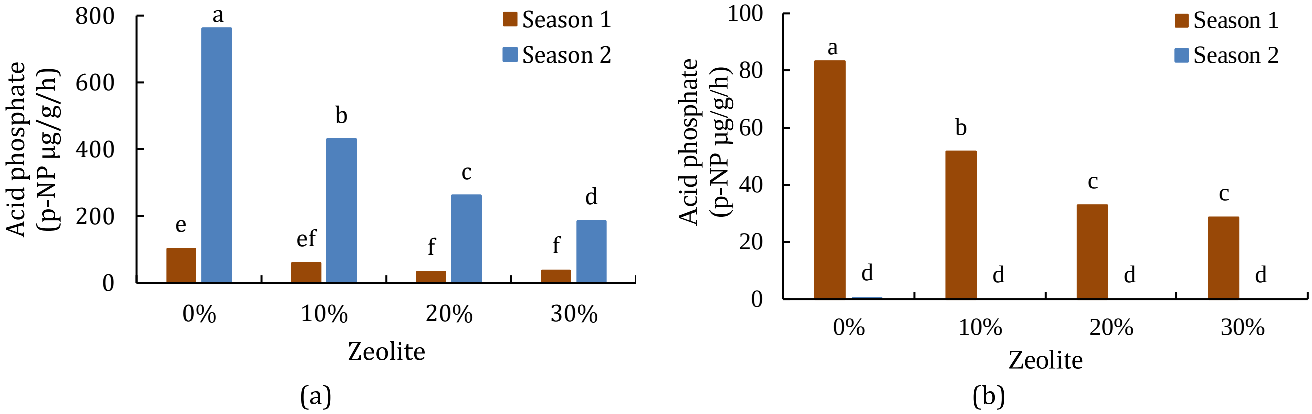


Figure 3. Effect of zeolite on the activity of phosphatase of potting soils (a) cabbage and (b) Swiss chard at the end of each season. Bars with the same letter are not significantly different

Effect of zeolite on β-glucosidase activity

Zeolite is an inorganic soil amendment, and the application of inorganic soil amendments has been linked to the reduction of soil organic carbon content, which negatively affects labile organic carbon fractions (Liu et al., 2017). The structural framework of zeolite comprises aluminium, silicon, and oxygen with no carbon (Keller et al., 2014). Therefore, the application of zeolite to the potted soils probably reduced soil organic matter content (Figure 4). However, soil organic carbon content was improved on all treatments compared to the baseline soil. This may be attributed to root remains and decomposed weeds left within the soil after harvest. Organic carbon cycling is associated with the activity of β-glucosidase (de Almeida et al., 2015). In this study, β-glucosidase activity results for the first season, Swiss chard, (Figure 5b) indicated a tentative reduction in β-glucosidase activity as soil organic carbon content reduced with increased zeolite application. The results from the first season for the activity of β-glucosidase for Swiss chard aligned with the findings of Amadou et al. (2020) who found that the application of inorganic soil amendments reduced the activity of β-glucosidase. The results were also in line with the findings of Eivazi and Tabatabai (1990) who found that the application of inorganic salts reduced the activities of α-glucosidase, α -galactosidase, β-glucosidase, and β-galactose. However, the correlation of soil β-glucosidase activity and organic carbon (%) for both seasons was negative, with cabbage-potting soils showing a strong negative correlation. In contrast, Swiss chard potting soils showed a weak correlation.

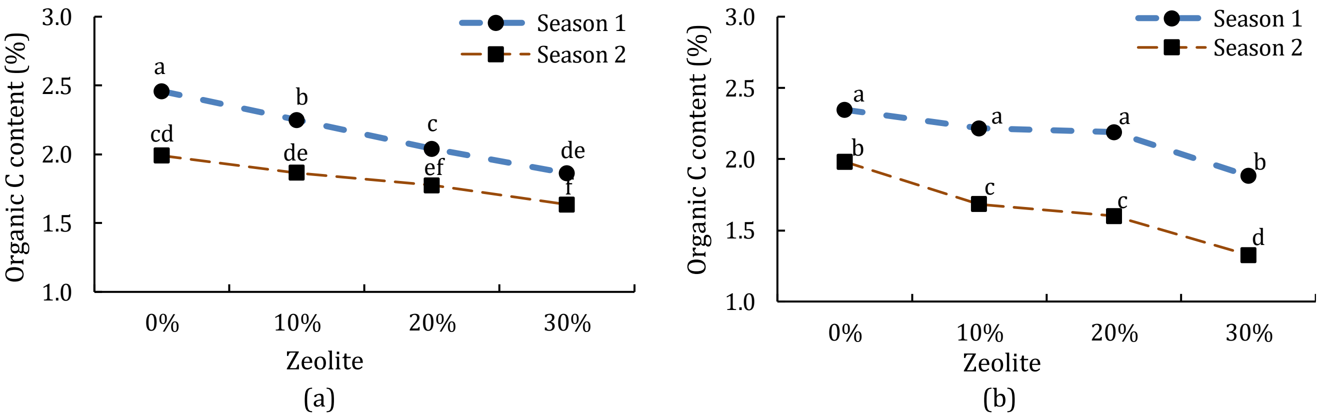
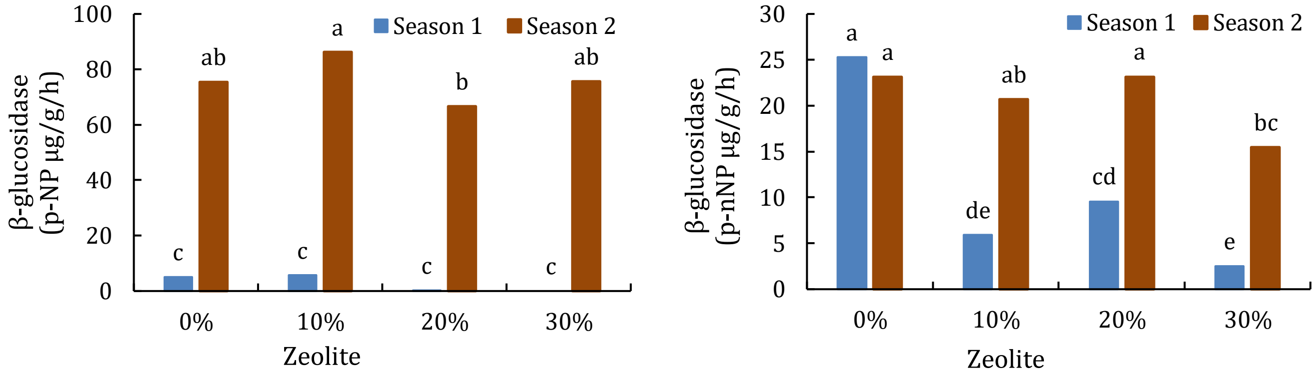


Figure 4. Effect of zeolite on soil organic C content (a) cabbage and (b) Swiss chard at the end of each season. Bars with the same letter are not significantly different

Apart from the reduction in soil organic carbon, with soil sieving, the increased zeolite application increased soil pH (Figure 1). Activity of β-glucosidase has also been noted previously to decrease with increased soil pH (Tiwari et al., 2019). In the second season, β-glucosidase activity results were inconclusive. The β-glucosidase activity showed a moderate negative correlation with soil pH for Swiss chard potted soils, while there was a weak negative correlation on cabbage potted soils (Table 2 and 3).

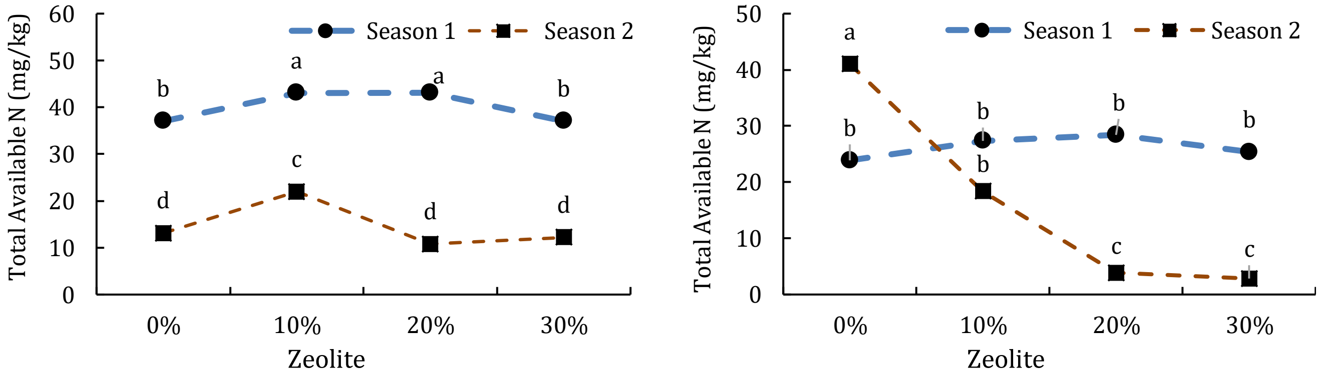


(a) (b)

Figure 5. Influence of zeolite on (a) cabbage and (b) Swiss chard at the end of each season. Bars with the same letter are not significantly different

Urease activity response to zeolite application

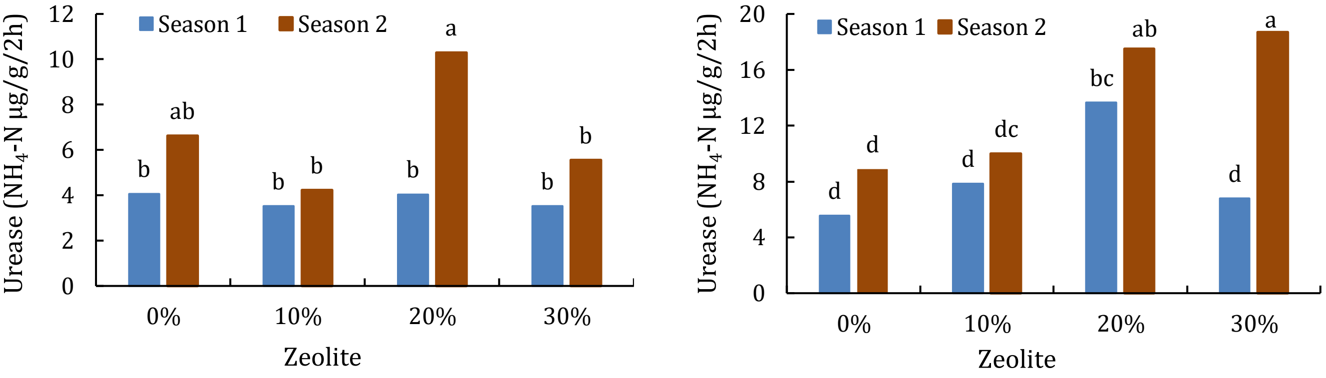
In this study, the N fertiliser used was urea ($CO(NH_2)_2$), which can be converted into NH_3 by urease (Abdi et al., 2006). The NO_3-N and NH_4-N dynamics and trends on the studied potting soils of cabbage and Swiss chard were comparable and are presented in Sindesi et al.'s (2023b) work. There was less N at the end of the second growing season in that work due to plant adsorption. The total plant available N (Figure 6) calculated in this study, with the exception of Swiss chard for the non-amended soil, was also greater in the first season than in the second season, which can be attributed to plant adsorption. These results can be linked to the yield results presented by Sindesi et al. (2023b), which showed reduced Swiss chard yields for the non-amended treatment in the second season. The reduced yields of the treatment were due to reduced plant growth and, therefore, a reduction in plant N utilisation.



(a) (b)

Figure 6. Effect of zeolite on total plant available nitrogen (a) cabbage and (b) Swiss chard at the end of each season. Bars with the same letter are not significantly different.

The activity of urease (Figure 7) generally remained constant on cabbage-potted soils, with exceptions. The activity increased with increased zeolite application in both seasons on Swiss chard potted soils. Enzyme urease in the soil is involved in the hydrolyses of urea or the cycling of N (Miśkowiec and Olech, 2020). Furthermore, urease activity in the cabbage potting soils showed no significant correlations with the observed soil chemical parameters (Table 2). However, in the Swiss chard potting soils urease activity showed a positive correlation with soil pH, and negative correlations with total plant available N, NH_4-N, and soil organic carbon content. The activity of urease has been linked with the availability of substrate (Vilar and Ikuma, 2021). Furtak and Gałązka (2019) suggest that using inorganic or conventional fertilisers reduces urease activity. In this study, this was not the case as the application of inorganic zeolite generally did not influence urease activity on the cabbage potting soils. In contrast, on Swiss chard potting soils, urease activity was increased. This observation suggests that soil enzyme activity may be influenced by plant species, particularly because different plant species drive different changes in soil nutrients (Li et al., 2021). Hoult and McGarity (1986) also found that the type, height, age, and canopy of pastures influenced the urease activity of the underlying soil. Yin et al. (2021) also found that soil enzyme activities varied among vegetation types. Additionally, zeolite is an inorganic soil amendment that improves soil physical conditions but is not a fertiliser.

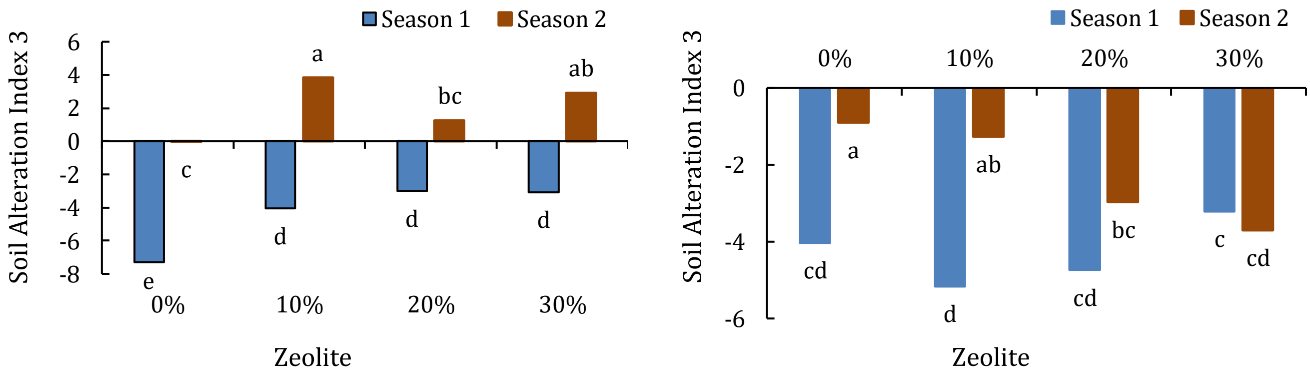


(a) (b)

Figure 7. Urease activity changes with increased applications of zeolite (a) cabbage and (b) Swiss chard at the end of each season. Bars with the same letter are not significantly different.

Alteration scores of zeolite-amended sandy potting soils

Soil enzyme activity is an important factor in assessing soil health. However, the enzymes are substrate-specific and individual activities do not indicate the total biological activity within soils (van Huyssteen et al., 2020). Using numeric indexes based on a combination of enzyme activities has proven beneficial (Igalavithana et al., 2017). The enzyme Alteration Index Three (AI3) has been used to combine and balance the activities of β-glucosidase, acid phosphatase, and urease into scores which reflect the degree of positive and negative changes (van Huyssteen et al., 2020). The AI3 results of the first season from the cabbage-potted soils tended to become less negative with the application of zeolite (Figure 8a). At the end of the second season, all the zeolite-amended treatments had positive AI3 scores, and the control treatment also reduced negativity. The more negative the AI3 score, the better is the soil quality (Meyer et al., 2014).



(a) (b)

Figure 8. Alteration index scores of soils amended with different levels of zeolite (a) cabbage and (b) Swiss chard at the end of each season. Bars with the same letter are not significantly different.

The AI3 scores observed from the Swiss chard potted soils in the first growing season decreased negativity with increased zeolite application. The non-amended soil was not significantly different from the 10% zeolite-amended soil. At the end of the second growing season, the negativity of the AI3 scores increased with the zeolite application. Meyer et al. (2014), indicated that the overutilization and/or detrimental alteration of the soil will result in AI3 values that are higher. Gosh et al. (2020) also found greater values of AI3 scores in soils that lacked organic matter. These results, therefore, suggest that the application of zeolite positively impacted the soil fertility of Swiss chard potted soils. This contradicted the second-season cabbage soil results when comparing the trends observed from the soil carbon results with those of AI3. There was a negative correlation between AI3 and soil carbon (%) for both cabbage and Swiss chard potted soils, and the correlation on cabbage potting soils was significant (Table 2), while that of Swiss chard was not significant (Table 3).

Conclusion

This study examined the effects of zeolite application on soil enzyme activities in a greenhouse setting. While valuable insights were gained, the findings also highlight the need for further research. Zeolite impacted soil enzyme activities differently depending on the vegetable species cultivated, with Swiss chard and cabbage exhibiting distinct responses. Notably, the reduction in soil organic matter due to zeolite application likely influenced enzyme activity. Zeolite's influence on individual enzyme activities was mixed. Acid phosphatase activity decreased, possibly due to altered soil pH. Beta-glucosidase activity showed a tentative reduction, potentially linked to lower organic carbon content. Interestingly, urease activity increased in Swiss chard soils but remained constant in cabbage soils, suggesting plant species-specific responses. Overall enzyme activity, as reflected by AI3 scores, improved in cabbage soils with zeolite application, indicating enhanced soil quality. However, Swiss chard soils exhibited mixed AI3 responses. Complex interactions were observed between enzyme activities and soil chemical parameters, underlining the need for further investigation.

Limitations to the study include the focus on a single soil type (sandy) and two vegetable species. Investigating the effects on other soil types and plant communities would provide a broader understanding. Additionally, the two-year research period may not fully capture the long-term effects of zeolite application. Further mechanistic studies are needed to understand how zeolite influences soil microbial communities and their enzyme production. Overall, this study demonstrates that zeolite application has the potential to influence soil enzyme activities, but the effects are plant species-dependent and require further exploration to optimize its use as a soil amendment

Acknowledgement

The National Research Foundation (NRF) of South Africa is acknowledged by the authors for providing financial assistance for the study (Grant Number 114405).

References

Abdi, Gh., Khosh-Khui, M., Eshghi, S., 2006. Effects of natural zeolite on growth and flowering of strawberry (Fragariaxananassa Duch.). *International Journal of Agricultural Research* 1(4): 384-389.

Al, C., Sun, J.W., Wang, X.B., Liand, G.Q., He, P., Zhou, W., 2015. Advances in the study of the relationship between plant rhizodeposition and soil microorganism. *Journal of Plant Nutrition and Fertilizers* 21(5): 1343-1351. [in Chinese].

Albano, X., Whitmore, A.P., Sakrabani, R., Thomas, C.L., Sizmur, T., Ritz, K., Harris, J., Pawlett, M., Watts, C., Haefele, S.M., 2023. Effect of different organic amendments on actual and achievable yields in a cereal-based cropping system. *Journal of Soil Science and Plant Nutrition* 23: 2122–2137.

Alkorta, I., Aizpurua, A., Riga, P., Albizu, I., Amézaga, I., Garbisu, C., 2003. Soil enzyme activities as biological indicators of soil health. *Reviews on Environmental Health* 18(1): 65-73.

Asadishad, B., Chahal, S., Akbari, A., Cianciarelli, V., Azodi, M., Ghoshal, S., Tufenkji, N., 2018. Amendment of agricultural soil with metal nanoparticles: effects on soil enzyme activity and microbial community composition. *Environmental Science and Technology* 52(4): 1908-1918.

Celestina, C., Hunt, J.R., Sale, P.W., Franks, A.E., 2019. Attribution of crop yield responses to application of organic amendments: A critical review. *Soil and Tillage Research* 186: 135-145.

de Almeida, R.F., Naves, E.R., da Mota, R.P., 2015. Soil quality: Enzymatic activity of soil β-glucosidase. *Global Journal of Agricultural Research and Reviews* 3(2): 146-450.

de Campos Bernardi, A.C., Oliviera, P.P.A., de Melo Monte, M.B., Souza-Barros, F., 2013. Brazilian sedimentary zeolite use in agriculture. *Microporous and Mesoporous Materials* 167: 16-21.

Dick, C.F., Dos-Santos, A.L.A., Meyer-Fernandes, J.R., 2011. Inorganic phosphate as an important regulator of phosphatases. *Enzyme Research* Article ID 103980.

Eivazi, F., Tabatabai, M.A., 1990. Factors affecting glucosidase and galactosidase activities in soils. *Soil Biology and Biochemistry* 22(7): 891-897.

Fujino, C., Wada, S., Konoike, T., Toyota, K., Suga, Y., Ikeda, J.I., 2008. Effect of different organic amendments on the resistance and resilience of the organic matter decomposing ability of soil and the role of aggregated soil structure. *Soil Science and Plant Nutrition* 54(4): 534-542.

Furtak, K., Gałązka, A., 2019. Enzymatic activity as a popular parameter used to determine the quality of the soil environment. *Polish Journal of Agronomy* 37: 22-30.

Ghosh, A., Singh, A.B., Kumar, R.V., Manna, M.C., Bhattacharyya, R., Rahman, M.M., Sharma, P., Rajput, P.S., Misra, S., 2020. Soil enzymes and microbial elemental stoichiometry as bio-indicators of soil quality in diverse cropping systems and nutrient management practices of Indian Vertisols. *Applied Soil Ecology* 145: 103304.

Guangming, L., Xuechen, Z., Xiuping, W., Hongbo, S., Jingsong, Y., Xiangping, W., 2017. Soil enzymes as indicators of saline soil fertility under various soil amendments. *Agriculture, Ecosystems & Environment* 237: 274-279.

Hoult, E.H., McGarity, J.W., 1986. The measurement and distribution of urease activity in a pasture system. *Plant and Soil* 93: 359-366.

Howa, J.D., Lott, M.J., Ehleringer, J.R., 2014. Isolation and stable nitrogen isotope analysis of ammonium ions in ammonium nitrate prills using sodium tetraphenylborate. *Rapid Communications in Mass Spectrometry* 28(13): 1530-1534.

Icoz, I., Stotzky, G., 2008. Fate and effects of insect-resistant Bt crops in soil ecosystems. *Soil Biology and Biochemistry* 40(3): 559-586.

Igalavithana, A.D., Farooq, M., Kim, K.H., Lee, Y.H., Qayyum, M.F., Al-Wabel, M.I., Lee, S.S., Ok, Y.S., 2017. Determining soil quality in urban agricultural regions by soil enzyme-based index. *Environmental Geochemistry and Health* 39: 1531-1544.

Kakar, K., Xuan, T.D., Noori, Z., Aryan, S., Gulab, G., 2020. Effects of organic and inorganic fertilizer application on growth, yield, and grain quality of rice. *Agriculture* 10(11): 544.

Kandeler, E., Gerber, H., 1988 Short-term assay of soil urease activity using colorimetric determination of ammonium. *Biology and Fertility of Soils* 6: 68-72.

Kanté, M., Riah-Anglet, W., Cliquet, J.B., Trinsoutrot-Gattin, I., 2021. Soil enzyme activity and stoichiometry: Linking soil microorganism resource requirement and legume carbon rhizodeposition. *Agronomy* 11(11): 2131.

Kaurin, A., Cernilogar, Z., Lestan, D., 2018. Revitalisation of metal-contaminated, EDTA-washed soil by addition of unpolluted soil, compost and biochar: Effects on soil enzyme activity, microbial community composition and abundance. *Chemosphere* 193: 726-736.

Keller, T.C., Isabettini, S., Verboekend, D., Rodrigues, E.G., Pérez-Ramírez, J., 2014. Hierarchical high-silica zeolites as superior base catalysts. *Chemical Science* 5(2): 677-684.

Li, Y., Han, C., Sun, S., Zhao, C., 2021. Effects of tree species and soil enzyme activities on soil nutrients in dryland plantations. *Forests* 12(9): 1153.

Liu, Z., Rong, Q., Zhou, W., Liang, G., 2017. Effects of inorganic and organic amendment on soil chemical properties, enzyme activities, microbial community and soil quality in yellow clayey soil. *PLOS ONE* 12(3): e0172767.

Margalef, O., Sardans, J., Fernández-Martínez, M., Molowny-Horas, R., Janssens, I.A., Ciais, P., Goll, D., Richter, A., Obersteiner, M., Asensio, D. and Peñuelas, J., 2017. Global patterns of phosphatase activity in natural soils. *Scientific Reports* 7: 1337.

Mazorra, M.T., Rubio, J.A., Blasco, J., 2002. Acid and alkaline phosphatase activities in the clam Scrobicularia plana: kinetic characteristics and effects of heavy metals. *Comparative Biochemistry and Physiology Part B: Biochemistry and Molecular Biology* 131(2): 241-249.

Meena, A., Rao, K.S., 2021. Assessment of soil microbial and enzyme activity in the rhizosphere zone under different land use/cover of a semiarid region, India. *Ecological Processes* 10: 16.

Meyer, A.H., Wooldridge, J., Dames, J.F., 2014. Relationship between soil alteration index three (AI3), soil organic matter and tree performance in a 'Cripps Pink'/M7 apple orchard. *South African Journal of Plant and Soil* 31(3): 173-175.

Miśkowiec, P., Olech, Z., 2020. Searching for the correlation between the activity of urease and the content of nickel in the soil samples: The role of metal speciation. *Journal of Soil Science and Plant Nutrition* 20: 1904-1911.

Munir, A., Nawaz, S., Bajwa, M.A., 2012. Farm manure improved soil fertility in mungbean-wheat cropping system and rectified the deleterious effects of brackish water. *Pakistan Journal of Agriculture Sciences* 49(4): 511–519.

Nannipieri, P., Giagnoni, L., Landi, L., Renella, G., 2011. Role of Phosphatase Enzymes in Soil. In: Phosphorus in Action: Biological Processes in Soil Phosphorus Cycling. Soil Biology. Bünemann, E., Oberson, A., Frossard, E., (Eds.). Vol 26. Springer, Berlin, Heidelberg, pp. 215-243.

Non-Affiliated Soil Analysis Work Committee, 1990. Handbook of standard soil testing methods for advisory purposes. Soil Science Society of South Africa, Pretoria.

Nur Aainaa, H., Haruna Ahmed, O., Ab-Majid, N.M., 2018. Effects of clinoptilolite zeolite on phosphorus dynamics and yield of Zea Mays L. cultivated on an acid soil. *PLOS ONE* 13(9): e0204401.

Okalebo, J.R., Gathua, K.W., Woomer, P.L., 2002. Laboratory methods of soil and plant analysis: A working manual. Second edition. Sacred African Publishers, Nairobi, Kenya.

Onyango, M.S., Kuchar, D., Kubota, M., Matsuda, H., 2007. Adsorptive removal of phosphate ions from aqueous solution using synthetic zeolite. *Industrial & Engineering Chemistry Research* 46(3): 894-900.

Pabalan, R.T., Bertetti, F.P., 2001. Cation-exchange properties of natural zeolites. *Reviews in Mineralogy and Geochemistry* 45(1): 453-518.

Ramesh, V., Jyothi, J.S., Shibli, S.M.A., 2015. Effect of zeolites on soil quality, plant growth and nutrient uptake efficiency in sweet potato (Ipomoea batatas L.). *Journal of Root Crops* 41(1): 25-31.

Sindesi, O.A., Lewu, M.N., Ncube, B., Mulidzi, R., Lewu, F.B., 2021. Mineral Composition of Potted Cabbage (Brassica Oleracea var, Capitata L.) grown in Zeolite amended sandy soil. *Agriculture (Pol'nohospodárstvo)* 67(3): 103-112.

Sindesi, O.A., Lewu, M.N., Ncube, B., Mulidzi, R., Lewu, F.B., 2023a. Residual effect of zeolite on soil exchangeable cations and cation exchange capacity in sandy soil cultivated with Swiss Chard. 35th International Conference on "Chemical, Biological and Environmental Engineering" (ICCBEE-22), 28-29 November 2023. Johannesburg, South Africa. pp. 36-39.

Sindesi, O.A., Ncube, B., Lewu, M.N., Mulidzi, A.R., Lewu, F.B., 2023b. Cabbage and Swiss chard yield, irrigation requirement and soil chemical responses in zeolite-amended sandy soil. *Asian Journal of Agriculture and Biology* 2023(1): 202111387.

Tejada, M., Gonzalez, J.L., García-Martínez, A.M., Parrado, J., 2008. Effects of different green manures on soil biological properties and maize yield. *Bioresource Technology* 99(6): 1758-1767.

Tiwari, R., Dwivedi, B.S., Sharma, Y.M., Sharma, A., Dwivedi, A.K., 2019. Activities of β-glucosidase, phosphatase and dehydrogenase as soil quality indicators: A review. *International Journal of Current Microbiology and Applied Sciences* 8(6): 834-846.

Tully, K., Sullivan, C., Weil, R., Sanchez, P., 2015. The state of soil degradation in Sub-Saharan Africa: Baselines, trajectories, and solutions. *Sustainability* 7(6): 6523-6552.

van Huyssteen, I., Mulidzi, A.R., Meyer, A.H., Wooldridge, J., 2020. Alteration index three facilitates interpretation of ß-Glucosidase, acid-phosphatase and urease activities in soils irrigated with diluted winery wastewater. *South African Journal of Enology and Viticulture* 41(2): 238-244.

Vilar, R.P., Ikuma, K., 2021. Adsorption of urease as part of a complex protein mixture onto soil and its implications for enzymatic activity. *Biochemical Engineering Journal* 171: 108026.

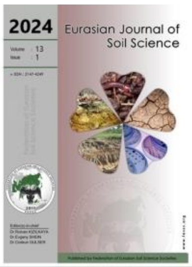
Walkley, A., Black. I.A., 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chronic acid titration method. *Soil Science* 37(1): 29-38.

Yin, R., Deng, H., Wang, H.L., Zhang, B., 2014. Vegetation type affects soil enzyme activities and microbial functional diversity following re-vegetation of a severely eroded red soil in sub-tropical China. *Catena* 115: 96-103.

Eurasian Journal of Soil Science 2024, 13(4), 294 - 302

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



Response of β-glucosidase enzyme activity of soil to biochar applications in a crop rotation at Blacksea agroecosystem

Murat Birol [a,*], Hikmet Günal [b]

[a] Black Sea Agricultural Research Institute, 55300 Samsun, Türkiye
[b] Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Harran University, 63290 Şanlıurfa, Türkiye

Article Info
Received : 28.12.2023
Accepted : 04.06.2024
Available online: 07.06.2024

Author(s)
M.Birol *
H.Günal

* Corresponding author

Abstract

The use of biochar has emerged a potentially effective approach to improve soil function and promote crop performance. However, the specific impact of biochar on β-glucosidase enzyme activity (BGA) within crop rotation systems in the Black Sea agroecosystem requires further investigation. This study was conducted to determine the effects of rice husk biochar (RHB) and poultry manure biochar (PMB) on BGA in soils. Six biochar doses (0-control, 10, 20, 30, 40 and 50 t ha^{-1}) were applied at the beginning of two wheat-cabbage red pepper rotation periods. The mean BGA at second rotation (73.71 µg pNP g^{-1}) was significantly lower compared to the BGA of the first period (93.39 µg pNP g^{-1}). The BGA value in control (94.51 µg pNP g^{-1}) decreased with increasing biochar application doses (76.05 µg pNP g^{-1}, 50 t ha^{-1}) treatment. The mean BGA value in PMB treatment was slightly higher than that of RHB, but it was not statistically different between two biochar types. However, the decrease in BGA value (25.0%) in the highest RHB dose compared to control was more than two-fold compared to the decrease in PMB application (12.1%). The difference in carbon/nitrogen ratio between RHB and PMB can be attributed to the variation in BGA values observed at the application of same biochar doses. The decrease in BGA over the course of the two rotation cycles implies that biochar may have a long-term influence on soil carbon cycling.

Keywords: Biochar, Biochar type, Poultry manure, Rice husk, Crop Rotation, β-glucosidase.

Introduction

Biochar, a carbonaceous substance produced through the thermal processing of biomass at high temperatures, has gained significant interest as a soil amendment for enhancing soil fertility and mitigating atmospheric carbon levels (Günal et al., 2019; Abhishek et al., 2022). An abundance of studies has been attempted to determine the impacts of biochar on the physical, chemical, and biological properties of soils. A recent comprehensive review analyzing 26 global meta-analyses (Schmidt et al., 2022; Long and Dung, 2023) provides evidence that biochar application has a positive overall impact on various agronomic parameters, including crop yield, root biomass, water use efficiency, microbial activity, soil organic carbon, and greenhouse gas emissions. The findings of this review provide strong evidence supporting the overall positive impact of biochar on the aforementioned parameters. However, the impact of incorporating biochar into soil enzyme depends on factors such as the type of feedstock and the pyrolysis temperature employed during biochar production, as well as the variability in soil texture (Feng et al., 2023). The meta-analysis revealed that the use of biochar in research examining soil organic carbon (SOC) has consistently resulted in a significant increase in SOC levels, irrespective of variations in feedstock, pyrolysis temperature, and soil types. In particular, the application of wood and herbs derived biochars led to the highest increase in SOC compared to the manure and agricultural residues. In general, biochars produced at high temperatures have a greater positive impact

: https://doi.org/10.18393/ejss.1497455
: https://ejss.fesss.org/10.18393/ejss.1497455
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

on SOC as compared to the biochars produced at lower and medium temperatures. Furthermore, the addition of biochar had a more pronounced effect on SOC in loamy and clay soils that the sandy soils (Gross et al., 2021).

The effect of biochar applications on soil enzymes has garnered significant attention, as enzymes play a vital role in nutrient cycling and organic matter decomposition in soil ecosystems (Wojewódzki et al., 2022; Rahmanian et al., 2023). The enzymes are proteins that catalyze chemical reactions and are essential for the decomposition and mineralization of organic materials into nutrients that can be used by plants and other organisms. Soil enzymes are produced by soil microorganisms, and they are influenced by a variety of factors, including the type of soil, the amount of organic matter, the moisture content, and the temperature (Tabatabai, 1994; Burns et al., 2013).

The Black Sea agroecosystem consists of dynamic agricultural landscapes characterized by a prevalent practice of crop rotation (Gülser et al., 2021). Consequently, it is crucial to investigate the impact of biochar applications on the activity of specific soil enzymes. The β-glucosidase enzyme is important in the breakdown of cellulose, a major component of plants. Therefore, the activity of β-glucosidase enzyme is commonly used an indicator of the soil quality and high β-glucosidase e activity indicates that the soil has a high quality of soil organic matter (Adetunji et al., 2020; Acir et al., 2022). Previous studies have clearly revealed that the biochar is a promising material for improving soil quality and crop production (Günal and Erdem, 2021; Murtaza et al., 2022; Wang et al., 2023). However, the specific effects of biochar on β-glucosidase enzyme activity in crop rotation systems in the Black Sea region are not well understood. This study investigated the effects of rice husk and poultry manure biochar applications on β-glucosidase enzyme activity in soils under a wheat-pepper-red cabbage rotation. An in-depth investigation of the complex relationship between biochar, soil enzymes, and crop rotation practices offers significant knowledge and understanding regarding the improvement of soil management techniques to achieve sustainable and productive agricultural solutions within this ecologically diverse region. The ramifications of this research extend beyond the Black Sea region and have relevance for agricultural operations in agroecosystems globally. This will contribute to our understanding of the potential utilization of biochar to improve soil quality and increase crop yields.

Material and Methods

Study area

Field experiments were conducted in Bafra experimental Station Research and Application fields of the Black Sea Agricultural Research Institute in Samsun province, Turkey. Bafra Plain is located between 400 26' and 410 45' north latitude and 350 30'' and 360 11' east longitude. The research area has warm and dry summers and mild and rainy in winters, displaying the characteristic climatic attributes commonly observed in the Black Sea Region. The precipitation in the study area occurs mainly throughout the fall and winter seasons, whilst the summer and spring months have low precipitation.

The initial crop rotation commenced with the cultivation of winter wheat from November 2014 to July 2015, succeeded by the planting of red cabbage from July 2015 to February 2016, and concluded with the production of paste peppers from May 2016 to September 2016. Similarly, the second cycle of crop rotation commenced with the cultivation of winter wheat from November 2016 to July 2017. This was followed by the planting of red cabbage from July 2017 to January 2018, and ended with the cultivation of paste pepper from May 2018 to September 2018. The experimental design comprised the application of rice husk and poultry manure biochar in the main plots, whereas the sub plots consisted of six different biochar doses ranging from 0 to 50 tons per hectare (0, 10, 20, 30, 40 and 50 t ha^{-1}). At the beginning of the experiment, biochars were applied to the soil surface and subsequently incorporated to a depth of 15 cm in the experimental field using a disc harrow. were in the sub plots. The layout of the experiment was split plots in randomized blocks with 3 replications. The experiments were continued for 4 years. The experiments were conducted over a period of four years. The dimensions of the plots were 3.6 meters by 5.6 meters.

Details of the Crop Rotation and Agricultural Practices

In the experiment, a crop rotation system consisting of winter wheat, red cabbage, and paste red pepper, which is commonly used in the Bafra plain, was applied. Bread wheat (Canik 2003), red cabbage (Caballero F1), and paste red pepper (Yalova 28) were used in the crop rotation. This study was carried out over two crop rotations. The Canik 2003 wheat variety is a moderately late-maturing type with white spikes, long awns, and red-hard seeds. The Caballero F1 red cabbage variety has a maturation period of 130-140 days. Its fruit head structure is oval cylindrical with a waxy layer. The Yalova 28 red pepper variety is a dwarf-looking plant with low branching, abundant foliage, and is moderately early maturing.

The soil analysis results of the experimental field indicated that P and K concentrations were at sufficient levels; therefore, only ammonium sulfate ($(NH_4)_2.SO_4$ - 21% N, 24% S) was used as the nitrogen source for all the crops grown in the rotation.

Characteristics of Biochars

Biochars were produced using poultry manure received from poultry farms in the region and processing waste from intensively planted paddy rice in the Central Black Sea Region. The rice husk was obtained from a rice processing facility and subjected to pyrolysis at a temperature of 400 ºC. The poultry manure biochar utilized in this study originated from a commercial power generation facility. The pyrolysis process of poultry waste was carried out at 400 ºC.

Some chemical properties of biochars used in the experiments and soil physical and chemical properties of experimental field are given in Table 1. The pH and electrical conductivity (EC) values of biochars were measured in a solution containing a mixture of biochar and water at a ratio of 1:5 using a pH-EC meter (Thomas, 1996). Total carbon and total nitrogen contents were determined using an Elemental Analyzer instrument (EA 3000 Eurovector SpA, Milan, Italy).

Table 1. Some properties of the biochars and soil used in the experiment (Birol, 2020)

Properties	Soil	Rice Husk Biochar	Poultry Manure Biochar
pH	7.74	10.20	11.57
EC^1 (dS m^{-1})	0.35	3.20	4.28
Organic Matter (%)	2.01	N/A^2	N/A^2
Sand (%)	17.7	N/A^2	N/A^2
Clay (%)	47.5	N/A^2	N/A^2
Silt (%)	34.8	N/A^2	N/A^2
Texture Class	Clay	N/A^2	N/A^2
Total N (%)	0.14	0.45	0.88
Total C (%)	N/A^2	61.7	58.8
C:N	N/A^2	137.1	66.8

^{1}EC: Electrical Conductivity; ^{2}N/A = Not Applicable

Soil Sampling and Analysis

Soil samples were collected from a depth of 0-20 cm in each plot before to the application of biochar, as well as after the completion of the first and second rotation periods. Particle size distribution was determined using the hydrometer method in a sedimentation cylinder; with sodium hexametaphosphate as the dispersing agent (Gee and Bouder, 1986). The method employed to determine β-glucosidase enzyme activity (BGA) in soil samples was based on the protocol established by Eivazi and Tabatabai (1988). In the method, a 4 ml solution of hydroxyethyl aminomethane buffer at a pH of 12 and a 0.05 M 1 ml p-nitrophenyl β-Glucopyranoside solution were added to the 1 g sample. The samples were incubated at 37ºC for 60 minutes. The concentration of p-nitrophenol was quantified at 410 nm wavelength using a spectrophotometer and the BGA was reported as micrograms of p-nitrophenol per gram of dry sample. Soil reaction (pH) (Thomas, 1996) and electrical conductivity (EC) (Rhoades, 1996), were measured in 1:2 soil–water suspensions. Soil organic matter was analyzed by using the Walkley–Black dichromate oxidation procedure (Walkley and Black, 1934).

Data Analysis

The normality test of the data showed a normal distribution. The Levene's test was performed to confirm the equality of variances of BGA between replicated measurements. An analysis of variance (ANOVA) was conducted to assess the impact of rotation period, biochar type and biochar doses on BGA. The mean values of BGA in various treatments were grouped using the least significant difference test (LSD) at a significance threshold of 0.05. Correlation analysis was done for the determination of the relationships between some properties of soils and β-glucosidase enzyme activity. The statistical analyses were conducted using the SPSS (SPSS Inc., Chicago, IL, USA) statistical software (version 26.0, SPSS Inc., Chicago, IL, USA).

Results and Discussion

The biochars utilized in this study are derived from plant (rice husk) and animal (poultry manure) feedstocks that are readily accessible in the region and frequently used to examine the effects of biochar application on soil characteristics and plant growth. The chemical and physical properties of biochars indicated notable differences (Table 1). Poultry manure biochar (PMB) had higher pH and EC values, total nitrogen, available phosphorus, potassium, DTPA extractable iron, copper, zinc, and manganese, while total carbon content of rice husk biochar (RHB) is higher compared to the PMB. Rich nutrient content of PMB is consistent with the previous reports indicating that the plant-based biochars can be considered a good soil conditioner due the low content of extractable nutrients compared to the biochars produced from manure, which is rich in nutrients and may be used as a soil fertilizer and conditioner (Uchimiya et al., 2010; Clemente et al., 2018; Jaaf et al., 2022). The soil of the experimental field had a silty clay loam texture, slightly alkaline pH, low in salinity, calcareous, rich in available P, K and micronutrients. Mean sand, clay and silt contents of experimental soils were 17.7, 47.5 and 64.8%, respectively. Average soil pH was 7.74, EC was 0.353 dS m^{-1}; lime and organic matter contents were 7.45% and 2.01%. Average nitrogen, phosphorus and potassium contents of the experimental soils were 0.14%, 21.1 mg kg^{-1} and 267 mg kg^{-1}, respectively (Table 1).

The results for individual effects of rotation period, biochar type and biochar application rate on BGA, two- and three-way interactions among individual factors have been presented separately.

Effects of individual factors on β-glucosidase enzyme activity of soil

β-glucosidase enzyme activity (BGA) is an indicator of biological activity and is one of the most widely used indicators to determine the effect of land use changes or application of agricultural practices on organic matter content of soils (Acir et al., 2022). The effects of rotation period and biochar application dose on BGA were statistically significant ($p<0.01$), while biochar type regardless of biochar dose and rotation period had no effect on the activity of β-glucosidase (Table 2). Like our findings, Zhang et al. (2014) reported a notable impact of 2-year corn-soybean rotation on BGA, that was significantly higher ($p<0.05$) in reduced tillage soils under monoculture corn compared to the activity under corn-soybean rotation. The difference was attributed to the changes in the structure of microbial communities associated with plants used in the crop rotation system.

Table 2. The effects of individual factors and interactions on β-glucosidase enzyme activities of soils

Source	DF	Sum of Square	Mean Square	F	P
Rotation period (RP)	1	6971.640	6971.640	390.974	0.003**
Biochar type (BT)	1	21.813	21.813	0.292	ns
Biochar dose (BD)	5	2650.806	530.161	17.173	<0.001**
RP x BT	1	48.626	48.626	0.650	ns
RP x BD	5	177.606	35.521	1.151	ns
BT x BD	5	470.072	94.014	3.045	0.020*
RP*BT*BD	5	79.033	15.807	0.512	ns

**: significant at $p<0.01$, **: significant at $p<0.01$, ns: not significant; DF: Degrees of freedom

The variation in organic matter incorporated into the soil with different crops grown during crop rotation has resulted in a differentiation of the BGA in the soil (Figure 1). In the first rotation, organic matter content of soils consistently increased with the increased application doses of rice husk biochar. Although the increase was not statistically significant, the organic matter content in the control plots was 2.09%, rising to 2.34% at the highest biochar dose (Figure 1). A similar trend was observed with poultry manure applications. The organic matter content, which was 2.02% in the control plot, increased to 2.33% at the highest biochar dose. In the second rotation period, a similar pattern was observed with both types of biochar, where higher biochar doses corresponded to increased organic matter content in the soils, similar to the first period. The mean BGA at the end of the first rotation period (93.39 µg pNP g^{-1}) was significantly higher than the BGA value measured at the end of second rotation (73.71 µg pNP g^{-1}) (Figure 1). The decline in BGA value as biochar ages is a significant factor to consider when applying biochar to soils. This observation aligns with the findings reported in the studies conducted by Chen et al. (2016) and Yadav et al. (2019). Yadav et al. (2019) showed a decrease of 60% and 39% in the BGA in aged and fresh biochar soil mixture, respectively, compared to the control on the 90th day. Additionally, Chen et al. (2016) observed a decrease of 20% in BGA after 18 months of biochar application in soil, followed by a subsequent increase of 56%. According to Yadav et al. (2019), the decline in BGA with aging of biochar can be related to the sorption of the enzyme onto the surfaces of the biochar particles. Although biochars can sometimes stabilize enzymes and enhance their activity, they more frequently reduce enzyme activity due to substrate sorption or direct interactions with biochar's hydrophobic and surface properties. The sorption process involves various interactions, such as electrostatic, pH-controlled, hydrophobic, and physical interactions, which can either preserve the enzyme's structure and function or alter the active site, reducing activity (Swaine et al., 2013; Foster et al., 2018).

The correlation analysis for rice husk biochar and poultry manure biochar treatments reveals significant insights into the interplay between some of soil properties and BGA (Table 3). The variation in organic matter incorporated into the soil through different crops during crop rotation and biochar has notably impacted the BGA, as illustrated in Figure 1. For rice husk biochar, the results show a positive correlation between BGA and soil pH (r=0.202), indicating that an increase in soil pH may enhance enzyme activity. However, there is a very weak negative correlation with electrical conductivity (EC) (r = -0.006), suggesting that EC has little to no impact on BGA in this context. The significant negative correlation between BGA and organic matter content (r=-0.443) suggests that higher organic matter levels might suppress enzyme activity (Table 3). The negative correlation between organic matter and BGA for both biochar types indicates that while biochar applications increase soil organic matter, they may simultaneously reduce enzyme activity. This suppression could be due to the sorption of enzymes onto the biochar surface or changes in soil microbial activity dynamics (Foster et al., 2018). Similarly, in soils treated with poultry manure biochar, BGA shows a positive correlation with EC (r =0.357) and pH (r=0.094). These positive correlations suggest that both higher EC and pH levels might promote enzyme activity. Nonetheless, BGA is negatively correlated with organic matter content (r =-0.273), indicating a potential inhibitory effect of increased organic matter on enzyme activity (Table 3). This inhibitory effect may result from the biochar's influence on organic matter dynamics or direct enzyme adsorption, reducing the bioavailability of the enzymes.

Table 3. The results of correlation analysis between β-glucosidase enzyme activity (BGA) and some of soil properties

	Rice Husk Biochar				Poultry Manure Biochar			
	pH	EC	OM	BGA[1]	pH	EC	OM	BGA[1]
pH	1				1			
EC	-0.018	1			0.163	1		
OM	-0.128	0.389*	1		0.300	-0.017	1	
BGA	0.202	-0.006	-0.443*	1	0.094	0.357*	-0.273	1

*P<0.05; [1] BGA: β-glucosidase enzyme activity. EC: Electrical Conductivity, OM: Organic Matter

Despite a C/N ratio of 66.8 in poultry manure and 137.1 in rice husk biochar (Table 1), the mean BGA in rice husk biochar added soil (84.10 μg pNP g^{-1}) was slightly higher compared to the BGA in poultry manure biochar added soil (83.00 μg pNP g^{-1}) (Figure 1). However, the difference in BGA between biochar types was not statistically significant (p=0.618) (Table 2). In contrast to our findings, Günal et al. (2018) reported a substantial variation (p<0.01) in the activity of the BGA between different types of biochar. The application of biochar derived from bean harvest residue resulted in the highest BGA (20.17 μg pNP g^{-1}), while the rice husk biochar application yielded the lowest BGA activity (18.54 μg pNP g^{-1}). The apparent similarity in enzyme activity among three distinct solid phases, namely pine biochar, grass biochar, and agricultural soil, has been attributed to the presence of negative surface charges on both the solid phases and the enzymes, despite the notable difference in their respective surface areas (Foster et al., 2018).

The highest mean BGA was recorded in control (94.51 μg pNP g^{-1}), while the BGA value decreased with increasing biochar application doses and the lowest average BGA value was recorded in BD5 (76.05 μg pNP g^{-1}) treatment (Figure 1). Inconsistent results have been reported regarding the effects of biochar application on BGA values of soils. Due to the complexity of the interactions between enzymes and solid surfaces, the effects of biochar applications on enzyme activities in soils cannot be sufficiently explained. The changes in soil structure and nutrient diffusion rates, sorption of substrate, or enzymes are the possible causes of decrease in enzyme activities with biochar application in soils (Foster et al., 2018). The application of higher biochar doses probably increased the C/N ratio in soils and lead to slow mineralization of soil organic matter. Previous studies reported that soil extracellular enzyme activities involved in carbon and sulphur cycling were higher in low biochar application doses and reduced with increasing biochar application doses (Wang et al., 2015). Demisie et al. (2014) reported an increase in microbial activity in low biochar application doses and indicated that high microbial activity contributed to higher carbon mineralization. Biochar applications caused 8.3, 10.0, 14.9, 16.6 and 16.4% decrease in BGA value compared to control with BD1, BD2, BD3, BD4 and BD5 application doses, respectively (Figure 1).

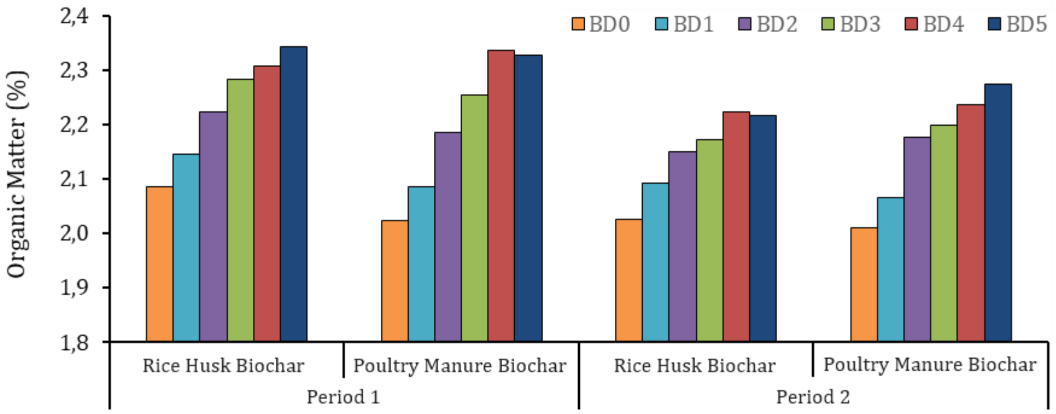


Figure 1. The effects of rotation period, biochar type and biochar dose interactions on organic matter content, %
(RP1: First rotation period, RP2: Second rotation period)
(Control; BD0: 0 t ha^{-1}, BD1: 10 t ha^{-1}, BD2: 20 t ha^{-1}, BD3: 30 t ha^{-1}, BD4: 40 t ha^{-1}, BD: 50 t ha^{-1})

The decrease in BGA can also be attributed to the presence of active functional groups on the surface and the pore space of biochar particles. The recorded decrease in BGA resulting from the application of biochar to soils has been attributed to the chemical modification or blocking of substrate binding sites by the applied biochar (Yoo and Kang, 2012; Chintala et al., 2014). The functional groups of biochar can selectively adsorb the enzyme substrate, potentially leading to a reduction in enzyme activity (Pokharel et al., 2018; Sial et al., 2022). Likewise, Foster et al. (2016) suggested that substantial sorption capacity of biochars could limit the accessibility of easily degradable carbon substrates for microorganisms, leading to reduced BGA in biochar applied soils. Consistent with our findings, Günal et al. (2018) showed that the application of 0.5, 1, 2 and 3% corn, bean and rice husk biochar to sandy loam and loamy soil resulted in a 3.7, 11.7, 16.4 and 16.4% decrease in mean BGA value compared to control, respectively. In their study, Moreno et al. (2022) compared the BGA activity of biochar derived from holm oak chips by slow pyrolysis at 600 °C with unamended soils in a crop rotation of barley-sunflower-wheat-barley-cameline under a Mediterranean agroecosystem. The researchers reported a notable increase in urease activity in biochar added soil, while the activities of BGA and protease were significantly reduced with the addition of biochar. The results revealed that biochar application to soil affected the activities of microbial community which is active in cellulose degradation and soil organic matter dynamics in soils. In contrast to our findings, Pérez-Guzmán et al. (2020) reported significantly higher ($P<0.05$) BGA values in soils incubated with corn and hardwood biochars produced under slow pyrolysis compared to the control group.

Effects of rotation period (RP), biochar type (BT) and biochar dose (BD) interactions on β-glucosidase enzyme activity

The statistical analysis revealed that the interaction between BT and BD had a significant influence on the BGA value ($p<0.05$), whereas the impact of other interactions on the BGA value was found to be insignificant (Table 2). The highest mean BGA value (94.77 µg pNP g^{-1}) in the RP x BT interaction was obtained in RP2 x rice husk biochar and the lowest average BGA value (73.44 µg pNP g^{-1}) was obtained in RP1 x rice husk treatment (Figure 2). The highest mean BGA value in RP x BD interaction was obtained in RP2x BD0 (104.70 µg pNP g^{-1}), while the lowest mean value was recorded in RP1 x BD5 (66.99 µg pNP g^{-1}) treatment (Figure. 2). The BGA value in BD1, BD2, BD3, BD4 and BD5 doses of rice husk biochar decreased by 12.1, 14.0, 21.7, 22.8, and 25.0%, respectively, compared to the control. The application of poultry manure biochar resulted in lower decreases of 4.0, 5.7, 7.4, 9.7 and 12.1% with respect to increasing doses of biochar. Overall, the difference in C/N ratio between rice husk biochar and poultry manure biochar is a major factor that contributes to the variation in BGA values observed at the application of the same biochar doses. The difference in C/N ratio has a significant impact on the way that biochar interacts with soil and microorganisms (Xu et al., 2023). Rice husk biochar is typically more resistant to decomposition and has a longer-term impact on soil carbon sequestration and BGA. Poultry manure biochar, on the other hand, is more easily decomposed and releases nutrients more quickly to plants, which may have a more immediate impact on BGA. The highest mean BGA value (100.07 µg pNP g^{-1}) in the BT x BD was obtained from rice husk x BD0 treatment, while the lowest average BGA value (75.04 µg pNP g^{-1}) was recorded in rice husk x BD5 treatment (Figure 2). The involvement of soil BGA, which is the rate-limiting enzyme, is crucial in the microbial metabolism, carbon (C) cycling, and sequestration of terrestrial ecosystems during the last phase of cellulose hydrolysis. In a study conducted by Raiesi and Khadem (2019), biochar derived from maize waste was incorporated into sandy loam and clayey soils at three different doses:

control (corn waste), 0.5% (corn waste biochar), and 1% (corn waste biochar), with the biochar being produced at a temperature of 600°C. Following a 90-day incubation period, the introduction of biochar resulted in a 81% increase in potential BG enzyme activity in sandy loam soil with only 1% biochar addition. Conversely, in clayey soil, the addition of 0.5% biochar led to a 10% reduction in potential BG enzyme activity, while addition of 1% biochar resulted in a 29% decrease.

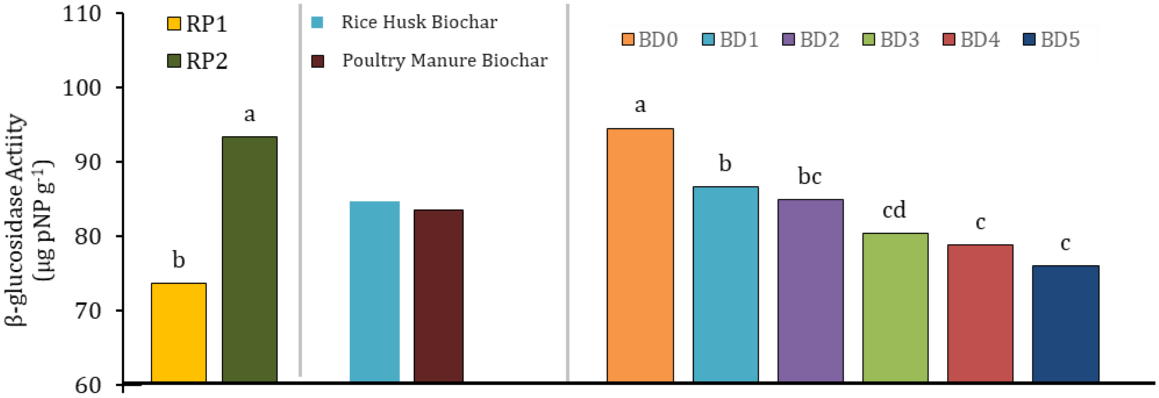


Figure 2. The effects of rotation period, biochar type and biochar doses on β-glucosidase enzyme activity (µg pNP g^{-1})
(RP1: First rotation period, RP2: Second rotation period)
(Control; BD0: 0 t ha^{-1}, BD1: 10 t ha^{-1}, BD2: 20 t ha^{-1}, BD3: 30 t ha^{-1}, BD4: 40 t ha^{-1}, BD: 50 t ha^{-1}).

The highest mean BGA value in the RP x BT x BD interaction was obtained in RP2 x Rice Husk Biochar x BD0 (112.23 µg pNP g^{-1}) and the lowest BGA value was in RP1 x Rice Husk Biochar x BD5 (65.45 µg pNP g^{-1}) interactions (Figure 3). The findings suggest that suggest that the effects of biochar on BGA may be complex and depend on several factors, including the type of biochar, the biochar dose, and the rotation period. Rice husk biochar was found to have a more pronounced effect on reducing BGA than poultry manure biochar. The difference is likely due to the higher C/N ratio of rice husk biochar, which makes it more resistant to decomposition. The slower decomposition rate of rice husk biochar means that it persists in the soil for longer, allowing for a more prolonged interaction with soil microbes and enzymes. The decrease in BGA over the course of the two rotation cycles suggests that biochar may have a long-term impact on soil carbon cycling. This is a promising finding, as it suggests that biochar could be used as a sustainable approach to improving soil health in crop rotation systems.

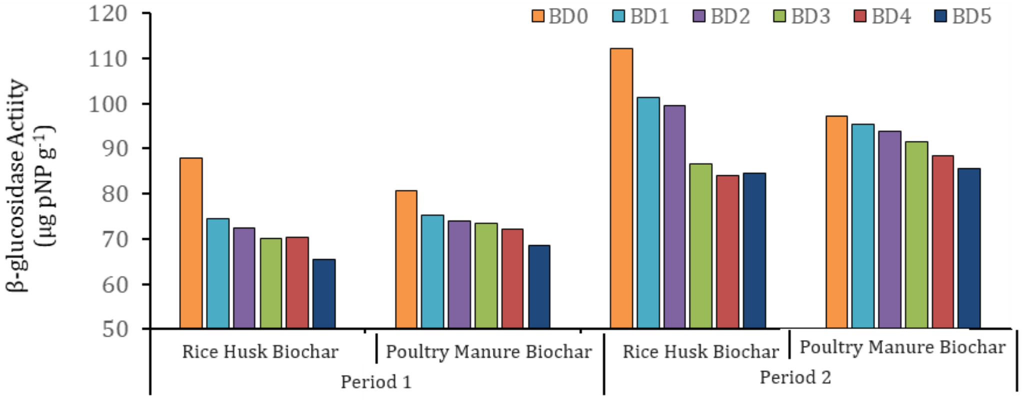


Figure 3. The effects of rotation period, biochar type and biochar dose interactions on β-glucosidase enzyme activity (BGA, µg pNP g^{-1}) (RP1: First rotation period, RP2: Second rotation period)
(Control; BD0: 0 t ha^{-1}, BD1: 10 t ha^{-1}, BD2: 20 t ha^{-1}, BD3: 30 t ha^{-1}, BD4: 40 t ha^{-1}, BD: 50 t ha^{-1})

Conclusion

This study investigated the effects of rice husk and poultry manure biochars on β-glucosidase enzyme activity (BGA) within a wheat-cabbage-red pepper crop rotation system in the Black Sea agroecosystem. Biochar application significantly impacted BGA, with rice husk biochar exhibiting a more pronounced effect on reducing activity compared to poultry manure biochar. This suggests a potential long-term influence of biochar on soil carbon cycling through its effect on organic matter decomposition. The observed decrease in BGA was statistically significantly for both biochar types, but the reduction was more than twice as high with rice husk biochar compared to poultry manure biochar at each application rate. We attribute this disparity to the higher C/N ratio of rice husk biochar, which promotes slower decomposition and a more persistent influence on soil carbon sequestration and BGA. Conversely, the lower C/N ratio of poultry manure biochar likely leads to faster decomposition and p nutrient release, potentially exerting a more direct influence on BGA in the short term. These findings suggest that rice husk biochar may be a more effective strategy for long-term soil carbon sequestration within this specific crop rotation system. In addition, the negative correlation between organic matter content and BGA suggests that increased organic matter may hinder enzyme activity, possibly due to biochar-mediated enzyme adsorption or alterations in soil microbial dynamics. However, further research is necessary to validate these results under various field conditions and across diverse crop rotations to elucidate the broader applicability of different biochar types on BGA activity.

Acknowledgement

This paper presents data derived from the PhD thesis of Dr. Murat Birol, who successfully finished his doctoral studies under the guidance of Dr. Hikmet Günal. The study was funded by the Turkish Ministry of Agriculture and Forestry, General Directorate of Agricultural Research and Policies (TAGEM-TSKAD/15A13/P03/03-01).

References

Abhishek, K., Srivastava, A., Vimal, V., Gupta, A. K., Bhujbal, S. K., Biswas, J. K., Singh, L., Ghosh, P., Pandey, A., Sharma, P, Kumar, M., 2022. Biochar application for greenhouse gas mitigation, contaminants immobilization and soil fertility enhancement: A state-of-the-art review. *Science of The Total Environment* 853: 158562.

Acir, N., Günal, H., Celik, I., Barut, Z. B., Budak, M., Kılıç, Ş., 2022. Effects of long-term conventional and conservational tillage systems on biochemical soil health indicators in the Mediterranean region. *Archives of Agronomy and Soil Science* 68(6): 795-808.

Adetunji, A.T., Ncube, B., Mulidzi, R., Lewu, F.B., 2020. Potential use of soil enzymes as soil quality indicators in agriculture. In: Frontiers in soil and environmental microbiology. Nayak, S.K., Mishra, B.B. (Eds.). Boca Raton: CRC Press. pp. 57-64.

Birol, M., 2020. Determining the effects of two different biochars on crop yields and soil quality. Tokat Gaziosmanpasa University, Graduate School of Natural and Applied Sciences, Department of Soil Science and Plant Nutrition. 273p. PhD Thesis. [in Turkish]

Burns, R.G., DeForest, J.L., Marxsen, J., Sinsabaugh, R.L., Stromberger, M.E., Wallenstein, M.D., Weintraub, M.N., Zoppini, A., 2013. Soil enzymes in a changing environment: current knowledge and future directions. *Soil Biology and Biochemistry* 58: 216-234.

Chen, J., Sun, X., Li, L., Liu, X., Zhang, B., Zheng, J., Pan, G., 2016. Change in active microbial community structure, abundance and carbon cycling in an acid rice paddy soil with the addition of biochar. *European Journal of Soil Science* 67(6): 857-867.

Chintala, R., Schumacher, T.E., Kumar, S., Malo, D.D., Rice, J.A., Bleakley, B., Chilom, G., Clay. D., Julson, J.L., Parierni k, S.K., Gu, Z.R., 2014. Molecular characterization of biochars and their influence on microbiological properties of soil. *Journal of Hazardous Materials* 279: 244-256.

Clemente, J.S., Beauchemin, S., Thibault, Y., MacKinnon, T., Smith, D., 2018. Differentiating inorganics in biochars produced at commercial scale using principal component analysis. *ACS Omega* 3(6): 6931-6944.

Demisie, W., Liu, Z., Zhang, M., 2014. Effect of biochar on carbon fractions and enzyme activity of red soil. *Catena* 121: 214-221.

Eivazi, F., Tabatabai, M.A., 1988. Glucosidases and galactosidases in soils. *Soil Biology and Biochemistry* 20(5): 601-606.

Feng, J., Yu, D., Sinsabaugh, R. L., Moorhead, D. L., Andersen, M. N., Smith, P., Song, Y., Li, X., Huang, Q., Chen, J., 2023. Trade-offs in carbon-degrading enzyme activities limit long-term soil carbon sequestration with biochar addition. *Biological Reviews* 98(4): 1184-1199.

Foster, E.J., Fogle, E.J., Cotrufo, M.F., 2018. Sorption to biochar impacts β-glucosidase and phosphatase enzyme activities. *Agriculture* 8(10): 158.

Foster, E.J., Hansen, N., Wallenstein, M., Cotrufo, M.F., 2016. Biochar and manure amendments impact soil nutrients and microbial enzymatic activities in a semi-arid irrigated maize cropping system. *Agriculture, Ecosystems & Environment* 233: 404-414.

Gee, G.W., Bouder, J.W., 1986. Particle size analysis. In: In: Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods, 5.1, Second Edition. Klute, A. (Ed.). American Society of Agronomy, Soil Science Society of America, WI, Madison, USA. pp. 383-411.

Gross, A., Bromm, T., Glaser, B., 2021. Soil organic carbon sequestration after biochar application: A global meta-analysis. *Agronomy* 11(12): 2474.

Gülser, C., Ekberli, İ., Gülser, F., 2021. Effects of deforestation on soil properties and organic carbon stock of a hillslope position land in Black Sea Region of Turkey. *Eurasian Journal of Soil Science* 10(4): 278 - 284.

Günal, E., Erdem, H., 2021. Effects of three different biochars enriched with dairy effluent on wheat growth. *Levantine Journal of Applied Sciences* 1(1): 1-15.

Günal, E., Erdem, H., Demirbaş, A. 2018. Effects of three biochar types on activity of β-glucosidase enzyme in two agricultural soils of different textures. *Archives of Agronomy and Soil Science* 64(14): 1963-1974.

Günal, H., Bayram, Ö., Günal, E., Erdem, H., 2019. Characterization of soil amendment potential of 18 different biochar types produced by slow pyrolysis. *Eurasian Journal of Soil Science* 8(4): 329 - 339.

Jaaf, S.M.M.A., Li, Y., Günal, E., El Enshasy, H.A., Salmen, S.H., Sürücü, A., 2022. The impact of corncob biochar and poultry manure on pepper (*Capsicum annuum* L.) growth and chemical properties of a silty-clay soil. *Saudi Journal of Biological Sciences* 29(4): 2998-3005.

Long, V.V., Dung, T.V., 2023. Reducing nitrogen fertilizer combined with biochar amendment improves soil quality and increases grain yield in the intensive rice cultivation system. *Eurasian Journal of Soil Science* 12(3): 222-228.

Moreno, J.L., Bastida, F., Díaz-López, M., Li, Y., Zhou, Y., López-Mondéjar, R., Li, Y., Zhou, Y., López-Mondéjar, R., Benavante-Ferraces, I., Rojas, R., Rey, A., García-Gil, J. C., Plaza, C. 2022. Response of soil chemical properties, enzyme activities and microbial communities to biochar application and climate change in a Mediterranean agroecosystem. *Geoderma* 407: 115536.

Murtaza, G., Ahmed, Z., Usman, M., 2022. Feedstock type, pyrolysis temperature and acid modification effects on physiochemical attributes of biochar and soil quality. *Arabian Journal of Geosciences* 15(3): 305.

Pérez-Guzmán, L., Lower, B.H., Dick, R.P., 2020. Corn and hardwood biochars affected soil microbial community and enzyme activities. A*grosystems, Geosciences & Environment* 3(1): e20082.

Pokharel, P., Kwak, J.H., Ok, Y.S., Chang, S.X., 2018. Pine sawdust biochar reduces GHG emission by decreasing microbial and enzyme activities in forest and grassland soils in a laboratory experiment. *Science of the Total Environment* 625: 1247-1256.

Rahmanian, M., Khadem, A., 2023. The effects of biochar on soil extra and intracellular enzymes activity. *Biomass Conversion and Biorefinery*

Raiesi, F. Khadem, A., 2019. Short-term effects of maize residue biochar on kinetic and thermodynamic parameters of soil β-glucosidase. *Biochar* 1(2): 213-227.

Rhoades, J.D., 1996. Salinity: Electrical conductivity and total dissolved solids. In: Methods of soil analysis. Part 3 Chemical methods. Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.). SSSA-ASA. Madison, WI, USA. pp. 417–435.

Schmidt, H.P., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T.D., Sánchez Monedero, M.A., Cayuela, M.L. 2021. Biochar in agriculture–A systematic review of 26 global meta-analyses. *GCB Bioenergy* 13(11): 1708-1730.

Sial, T.A., Shaheen, S.M., Lan, Z., Korai, P.K., Ghani, M.I., Khan, M.N., Syed, A.A., Ali, M.N.H.A., Abdelrahman, H., Ali, E.F., Rinkbele, J., Zhang, J., 2022. Addition of walnut shells biochar to alkaline arable soil caused contradictory effects on CO_2 and N_2O emissions, nutrients availability, and enzymes activity. *Chemosphere* 293: 133476.

Swaine, M., Obrike, R., Clark, J.M., Shaw, L.J. 2013. Biochar alteration of the sorption of substrates and products in soil enzyme assays. *Applied and Environmental Soil Science* Article ID 968682.

Tabatabai, M.A., 1994. Soil Enzymes. In: Methods of Soil Analysis Part 2 Microbiological and Biochemical Properties. Weaver, R.W., Angle, S., Bottomley, P., Bezdicek, D., Smith, S., Tabatabai, A., Wollum, A. (Eds.). SSSA-ASA. Madison, WI, USA. pp. 775-833.

Thomas, G.W., 1996. Soil pH and soil acidity. In: Methods of soil analysis. Part 3 Chemical methods. Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.). SSSA-ASA. Madison, WI, USA. pp. 475–490.

Uchimiya, M., Lima, I.M., Klasson, K.T., Wartelle, L.H., 2010. Contaminant immobilization and nutrient release by biochar soil amendment: roles of natural organic matter. *Chemosphere* 80(8): 935-940.

Walkley, A., Black, C.A., 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* 37(1): 29–38.

Wang, S., Gao, P., Zhang, Q., Shi, Y., Guo, X., Lv, Q., Wu, W., Zhang, X., Li, M., Meng, Q., 2023. Biochar improves soil quality and wheat yield in saline-alkali soils beyond organic fertilizer in a 3-year field trial. *Environmental Science and Pollution Research* 30(7): 19097-19110.

Wang, X., Song, D., Liang, G., Zhang, Q., Ai, C., Zhou, W., 2015. Maize biochar addition rate influences soil enzyme activity and microbial community composition in a fluvo-aquic soil. *Applied Soil Ecology* 96: 265-272.

Wojewódzki, P., Lemanowicz, J., Debska, B., Haddad, S.A., 2022. Soil enzyme activity response under the amendment of different types of biochar. *Agronomy* 12(3): 569.

Xu, W., Xu, H., Delgado-Baquerizo, M., Gundale, M. J., Zou, X., Ruan, H., 2023. Global meta-analysis reveals positive effects of biochar on soil microbial diversity. *Geoderma* 436: 116528.

Yadav, V., Jain, S., Mishra, P., Khare, P., Shukla, A.K., Karak, T., Singh, A.K., 2019. Amelioration in nutrient mineralization and microbial activities of sandy loam soil by short term field aged biochar. *Applied Soil Ecology*, 138: 144-155.

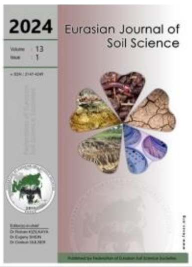
Yoo, G., Kang, H., 2012. Effects of biochar addition on greenhouse gas emissions and microbial responses in a short-term laboratory experiment. *Journal of Environmental Quality* 41(4): 1193-1202.

Zhang, B., Li, Y., Ren, T., Tian, Z., Wang, G., He, X., Tian, C., 2014. Short-term effect of tillage and crop rotation on microbial community structure and enzyme activities of a clay loam soil. Biology and Fertility of Soils 50: 1077-1085.

Eurasian Journal of Soil Science 2024, 13(4), 303 - 311

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



Sustainable agriculture through qanat systems in Karabakh: Water and soil characteristics in the context of climate change

Alovsat Guliyev [a,*], Tunzala Babayeva [b], Rahila Islamzade [a], Tariverdi Islamzade [a], Terlan Yelmarlı [a], Elnur Nesirov [c], Azade Aliyeva [b], Nergiz Ashurova [b]

[a] Institute of Soil Science and Agrochemistry, Baku, Azerbaijan
[b] Sumgayit State University, Sumgayit, Azerbaijan
[c] "Sukanal" Scientific-Research and Design Institute, Baku, Azerbaijan

Article Info

Received : 04.02.2024
Accepted : 23.06.2024
Available online: 03.07.2024

Author(s)

A.Guliyev *
T.Babayeva
R.Islamzade
T.Islamzade
T.Yelmarlı
E.Nesirov
A.Aliyeva
N.Ashurova

* Corresponding author

Abstract

This study investigates the water quality and soil characteristics associated with qanat systems in the Cebrail district of the Karabakh region, Azerbaijan. Qanat systems, traditional underground channels designed for water transport, play a crucial role in providing reliable water sources for drinking and irrigation. Water and soil samples were collected from seven qanat systems and analyzed for various physicochemical properties. Water quality parameters included pH, electrical conductivity, hardness, mineralization, and concentrations of calcium, magnesium, sodium, and other ions. Soil analyses focused on pH, electrical conductivity, organic matter content, salinization degree, and the presence of key ions like sulfate and nitrate. The results indicated that qanat water is generally of high quality, with pH levels suitable for both drinking and irrigation. However, some qanat systems exhibited high electrical conductivity and mineralization levels, suggesting potential salinity issues for sensitive crops. Soil samples showed favorable conditions for agriculture, with good pH levels, low salinity, and high organic matter content. The analysis revealed a significant interaction between water quality and soil characteristics, emphasizing the importance of integrated management practices. In the context of climate change, the sustainability of qanat systems is critical. Recommendations include regular monitoring of water and soil quality, soil amendments to mitigate salinity, efficient irrigation techniques, and the use of climate-resilient infrastructure. This study underscores the importance of qanat systems in arid and semi-arid regions and provides practical recommendations for sustainable land and water resource management, enhancing the socio-economic well-being of local communities.

Keywords: Qanat systems, agricultural impact, Karabakh region, soil and water management.

Introduction

The ancient qanat (kehriz) systems of the Karabakh region in Azerbaijan offer a fascinating insight into historical water management techniques and their relevance to contemporary water quality and soil health. These underground channels, engineered to transport water from aquifers to the surface, have been instrumental in sustaining agriculture and supporting local communities in arid and semi-arid regions for centuries (Guliyev, 2016; 2021). By providing a dependable water source, qanat systems have played a critical role in maintaining agricultural productivity and the livelihoods of those who depend on it (Nasiri and Mafakheri, 2015; Mansouri Daneshvar et al., 2023).

Water quality from qanat systems is essential for both drinking and irrigation. Studies have shown that water from these systems often remains high in quality due to natural filtration processes occurring as it flows through underground channels (Shams, 2014). Research conducted in Nakhchivan and other parts of

: https://doi.org/10.18393/ejss.1509552
: https://ejss.fesss.org/10.18393/ejss.1509552

Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

Azerbaijan supports this, indicating that qanat water is typically free from significant contamination, making it suitable for various uses. Similar observations have been made in other regions utilizing qanat systems, such as Iran, Jordan, Syria, and Oman, where water quality remains high despite challenging arid conditions (Lightfoot, 1996; Abudanh and Twaissi, 2010; Hamidian et al., 2015).Understanding the soil properties near qanat systems is equally important. The continuous supply of clean water from qanat systems can influence soil salinity and fertility, thereby impacting agricultural productivity. Research in various parts of Azerbaijan, including the Karabakh region, has shown that soils near qanat systems tend to have favorable properties for agriculture, with lower salinity levels and better nutrient content compared to other areas. This can be attributed to the regular and controlled irrigation provided by qanat water, which helps maintain soil health and reduces the accumulation of salts (Hamidian et al., 2015; Abadi et al., 2023).

The significance of water quality and soil properties becomes even more pronounced in the context of climate change. As global temperatures rise and precipitation patterns shift, the availability and quality of water resources are becoming critical concerns (Abbass et al., 2022; Telo da Gama, 2023). In Azerbaijan, where much of the freshwater comes from transboundary rivers and underground sources, ensuring the sustainability of qanat systems is vital for mitigating the impacts of climate change. Clean and reliable water sources like qanat systems are essential for adapting to changing environmental conditions and ensuring the long-term viability of agricultural practices (Guliyev, 2016; Guliyev, 2021; Pasha et al., 2023).

The agricultural activities supported by qanat systems in the Karabakh region are of particular socio-economic importance. The reliable water supply from these systems supports a variety of crops, contributing significantly to the livelihoods of local communities (Babayeva et al., 2024). The historical and cultural significance of qanat systems also adds to the heritage value of the region, making it important to preserve and study these ancient technologies (Koren and Bisesi, 2003).

This study represents a pioneering scientific investigation into the qanat systems of the Karabakh region. By evaluating the water quality and soil properties associated with these systems, this research aims to provide valuable insights into the sustainable management of water and soil resources in arid and semi-arid regions. The findings will contribute to a better understanding of how traditional water systems can be integrated with modern agricultural practices to enhance environmental conservation and sustainability efforts.

The objectives of this study are:

- To assess the physicochemical quality of water from qanat systems in the Cebrail district, Karabakh region of Azerbaijan, focusing on key parameters such as pH, electrical conductivity, hardness, mineralization, and the presence of various minerals and heavy metals.
- To evaluate the soil properties in areas adjacent to qanat systems, including pH, organic matter content, texture, and nutrient levels.
- To determine the relationship between water quality and soil characteristics, providing recommendations for sustainable land and water resource management in the face of climate change.

This research marks the first scientific study conducted in the Cebrail district, Karabakh region on this topic, underscoring its significance in the field of environmental and agricultural sciences. By filling existing knowledge gaps and providing practical recommendations, this study aspires to support sustainable development goals and enhance the livelihoods of communities dependent on these vital resources.

Material and Methods

Sample Collection

This study was conducted on 7 qanat systems in the Cebrail district, Karabakh region of Azerbaijan. Water and soil samples were collected from these qanat systems and their surrounding areas. The specific locations of the qanat systems were recorded using GPS coordinates to ensure precise documentation and repeatability of the study.

Water Sample Collection and Analysis

Water samples were collected directly from the qanat outlets using sterilized polyethylene bottles. Approximately 1 liter of water was collected from each qanat. The samples were immediately stored in cool, dark conditions to prevent any changes in water quality during transport to the laboratory.

In the laboratory, various water quality parameters were analyzed. The smell at 20°C was assessed by sensory evaluation, while colorfulness was measured using a colorimeter. Turbidity was determined with a nephelometer. The hydrogen ion concentration (pH) and electrical resistance at 25°C were measured using pH and EC meters. Water hardness was assessed through EDTA titration, and mineralization was calculated from the sum of all dissolved minerals. Dry residue was measured by evaporating the water sample and weighing the remaining solids. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations were analyzed using atomic absorption spectrophotometry (AAS), and sodium (Na^+) and potassium (K^+) were measured by flame photometry. Hydrocarbonate (HCO_3^-) levels were determined by titration with hydrochloric acid, while sulfate (SO_4^{2-}) was measured using a turbidimetric method. Chlorides (Cl^-) were assessed via the argentometric method, and ammonium nitrogen (NH_4^+-N) was measured using the Nesslerization method. Nitrates (NO_3^-) and nitrites (NO_2^-) were determined using a UV spectrophotometer and colorimetric method, respectively. Phosphates (PO_4^{3-}) were determined using a colorimetric method, fluorides (F^-) using an ion-selective electrode, and cyanides (CN^-) via a colorimetric method. All analyses were performed in triplicate to ensure accuracy and reliability (Rice and Bridgewater, 2012; Chambers, 2019).

Soil Sample Collection and Analysis

Soil samples were collected from the surface layer (0-20 cm) at multiple points surrounding each qanat system to obtain a representative sample. The samples were air-dried, ground, and passed through a 2 mm sieve to remove debris and large particles.

Various soil properties were analyzed to assess their quality. Soil pH was measured in a soil-to-water suspension using a pH meter, and electrical conductivity (EC) was determined using a conductometer. Humus content was assessed by the Walkley-Black method, and salinization degree was evaluated by measuring the EC of the soil extract. Sulfate (SO_4^{2-}) and nitrate (NO_3^-) ions were analyzed using turbidimetric and UV spectrophotometer methods, respectively. Carbonate (CO_3^{2-}) and hydrocarbonate (HCO_3^-) ions were measured by titration with hydrochloric acid. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions were quantified using AAS. Mechanical composition, including physically sand (>0,01 mm) and physically clay (<0,01 mm) fractions, was determined using the hydrometer method. All analyses were conducted in triplicate to ensure data reliability (Page et al., 1982; Carter and Gregorich, 2008).

Results and Discussion

Characteristics of Qanat Systems

The qanat systems studied in the Cebrail district of the Karabakh region exhibit a variety of characteristics, as detailed in Table 1. These systems, which range in length from 200 meters to 1500 meters, provide crucial water sources for both drinking and irrigation. The depth of the main wells and exit wells varies significantly, impacting the water extraction efficiency and overall sustainability of each system. Water consumption rates also differ, with some qanat systems delivering up to 275 liters per minute, demonstrating their significant capacity to support local agricultural activities.

Table 1. Characteristics of qanat Systems in the Cebrail District, Karabakh Region, Azerbaijan

Qanat No	Location	Name	Coordinates	Elevation (m)	Length (m)	No. of Wells	Depth of Main Well (m)	Depth of Exit Well (m)	Water Consumption (L/min)
1	Horovlu wilage	Asger kəhrizi	N 39.402079 E 47.095482	435	500	13	16	2,5	6
2	Horovlu wilage	Orta Kehriz	N 39.398508 E 47.096434	439	450	10	12	2,0	15
3	Center of Cebrail	Cinar Kehrizi	N 39.402266 E 47.025902	601	1500	20	30	2,5	1
4	Chereken willage	Taveka kəhrizi	N 39.415907 E 47.080623	532	1000	32	20	3,5	2
5	Horovlu kəndi	Şıxı kəhrizi	N 39.415849 E 47.080600	416	450	14	13	1,5	4
6	Horovlu willage	Xəlifə Kəhrizi	N 39.393335 E047.096304	433	850	16	17	2,5	11
7	Quycaq willage	Kuzey Kəhrizi	N 39.405364 E 47.145355	373	200	42	25	2,75	8

Water Quality of Qanat Systems

The analysis of water samples from the seven qanat systems reveals important insights into the physicochemical properties of the water. As shown in Table 2, the absence of odor at 20°C across all samples indicates the lack of organic contaminants that typically cause unpleasant smells. The colorfulness parameter was zero in most samples, except for Qanat No. 5, which exhibited minimal color, suggesting clear water with low turbidity in general.

The turbidity values, which range from 0.21 mg/L to 1.29 mg/L, show variations in suspended particles among the qanat systems. According to the World Health Organization (WHO, 2017) guidelines, turbidity should be below 5 NTU (Nephelometric Turbidity Units) for drinking water. All the qanat water samples meet this criterion, indicating that they are suitable for consumption in terms of clarity.

The pH levels, ranging from 6.83 to 7.70, are within the neutral to slightly alkaline range, which is considered ideal for both drinking and irrigation. The WHO (2017) recommends a pH range of 6.5 to 8.5 for drinking water, and all the qanat samples fall within this range, confirming their suitability for consumption.

Electrical conductivity (EC) values, ranging from 4040 µS/cm to 8280 µS/cm, indicate varying salinity levels. According to the Food and Agriculture Organization (FAO, 1985) standards, water with EC values below 700 µS/cm is considered good for irrigation, while values above 3000 µS/cm indicate potential salinity problems for sensitive crops. Most qanat systems exceed 3000 µS/cm, suggesting that while the water is generally usable, it requires careful management to avoid soil salinization.

Hardness levels ranged from 1.85 mmol/L to 3.60 mmol/L. The WHO (2017) classifies water with hardness above 1.5 mmol/L as moderately hard, and above 3.0 mmol/L as hard. Thus, some qanat samples can be considered hard, which may necessitate treatment for specific uses to prevent scaling in pipes and negative effects on crops.

Mineralization levels, indicating total dissolved solids (TDS), varied from 3404 mg/L to 7136 mg/L. The WHO guideline (WHO, 2017) for TDS in drinking water is 1000 mg/L. All the qanat water samples exceed this guideline, suggesting that while they may be suitable for irrigation, they might not be ideal for direct human consumption without treatment.

Table 2. Chemical properties of water samples from qanat systems

Water chemical properties	Qanat No						
	1	2	3	4	5	6	7
Smell at 20^0C	0	0	0	0	0	0	0
Colorfulness	0	0	0	0	5	0	0
The blur, mg/lt	0,26	0,30	0,45	1,29	0,21	0,77	0,44
pH	7,07	6,83	6,90	7,70	7,64	7,00	7,40
Electrical Conductivity, µS/cm	650,0	732,0	404,0	556,0	828,0	802,0	792,0
The hardness, mmol/l	295,0	350,0	185,0	230,0	360,0	300,0	300,0
Mineralization, mg/lt	537,9	640,5	340,4	440,1	713,6	669,6	617,6
Dry residue, mg/lt	416,0	488,0	225,0	324,0	537,0	524,0	483,0
Ca^{2+}, mg/lt	86,20	100,20	56,10	72,10	108,20	88,20	96,20
Mg^{2+}, mg/lt	19,50	24,30	10,90	12,20	21,90	19,50	14,60
$Na^+ + K^+$, mg/lt	30,60	36,60	14,50	27,80	54,00	69,50	54,30
HCO_3^-, mg/lt	244,0	305,0	231,8	231,8	353,8	292,8	268,4
SO_4^{2-}, mg/lt	147,0	165,0	18,0	76,0	159,0	174,0	153,0
Cl^-, mg/lt	1,40	1,40	1,40	8,90	14,50	17,40	23,00
NH_4^+-N, mg/lt	0,16	0,12	0,17	0,16	0,15	0,25	0,18
NO_3^--N, mg/lt	8,20	7,00	6,90	11,00	1,90	6,00	7,40
NO_2^--N, mg/lt	0,02	0,02	0,01	0,01	0.019	0.041	0.022
PO_4^{2-}, mg/lt	0,11	0,13	0,12	0,15	0,10	2,18	0,05
F^-, mg/lt	0,43	0,32	0,22	0,00	0,01	0.02	0,43
CN, mg/lt	0,007	0,002	0,001	0,002	0,000	0.002	0,003

In terms of individual ions, calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations ranged significantly. Calcium ranged from 5610 mg/L to 10820 mg/L, and magnesium ranged from 1090 mg/L to 2430 mg/L. According to WHO guidelines (WHO (2017), the recommended maximum levels for calcium and magnesium in drinking water are 75 mg/L and 50 mg/L, respectively. All samples exceed these limits, suggesting potential issues for direct consumption but remaining suitable for irrigation with proper management.

Sodium (Na^+) and potassium (K^+) levels also varied, with sodium and potassium combined concentrations ranging from 1450 mg/L to 6950 mg/L. High sodium levels can adversely affect soil structure and permeability when used for irrigation. WHO (2017) suggests a maximum sodium concentration of 200 mg/L for drinking water. Therefore, while the levels are high for direct human consumption, careful water management practices can mitigate adverse effects on agricultural soils.

The concentrations of bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), and chloride (Cl^-) were measured. Bicarbonate levels ranged from 2318 mg/L to 3538 mg/L, sulfate from 180 mg/L to 1740 mg/L, and chloride from 140 mg/L to 2300 mg/L. WHO guidelines (WHO (2017) recommend maximum concentrations of 250 mg/L for sulfate and 250 mg/L for chloride in drinking water. Some qanat systems exceed these limits, indicating the necessity for treatment before human consumption.

Ammonium nitrogen (NH_4^+-N) levels were found to be low across all samples, within the acceptable limits for drinking water. Nitrate (NO_3^-) and nitrite (NO_2^-) concentrations varied but remained within WHO guidelines (WHO (2017) of 50 mg/L and 3 mg/L, respectively, for drinking water.

Phosphate (PO_4^{3-}) levels were generally low, except for Qanat No. 6, which showed an elevated level of 2.18 mg/L. Fluoride (F^-) concentrations were within safe limits for all samples, and cyanide (CN^-) levels were negligible.

Soil Quality Around Qanat Systems

The soil samples collected from the vicinity of the qanat systems reveal a range of physicochemical properties, as shown in Table 3. The pH levels, which ranged from 7.10 to 7.90, indicate slightly alkaline conditions that are conducive to most agricultural activities. Electrical conductivity (EC) values, which measure soil salinity, were relatively low across all samples, ranging from 0.078 dS/m to 0.096 dS/m, indicating minimal salinity issues.

Organic matter content in the soils was found to be between 4.40% and 4.90%, reflecting good soil fertility and structure, which is beneficial for crop growth. The degree of salinization was low, with values ranging from 0.02% to 0.09%, indicating that there is minimal risk of salt accumulation in the soil, which is crucial for maintaining soil health and agricultural productivity.

Sulfate concentrations in the soil varied between 8500 mg/kg and 10100 mg/kg. These levels are generally acceptable but require monitoring to prevent potential negative impacts on soil and plant health. Nitrate concentrations ranged from 2000 mg/kg to 5800 mg/kg, indicating adequate levels of available nitrogen for plant growth.

Table 3. Physicochemical properties of soil samples around qanat systems

Soil Physicochemical Properties	Qanat No 1	2	3	4	5	6	7
pH	7,70	7,10	7,60	7,20	7,90	7,60	7,60
EC, dS/m	0,89	0,87	0,79	0,96	0,84	0,88	0,78
Organic matter, %	4,90	4,80	4,60	4,40	4,70	4,70	4,80
Salinization degree, %	0,09	0,02	0,08	0,07	0,09	0,08	0,09
SO_4^{2-}, mg/kg	100,00	85,00	90,00	87,00	89,00	101,00	89,00
NO_3^-, mg/kg	54,00	20,00	44,00	58,00	56,00	54,00	44,00
CO_3^-, mg/kg	0	0	0	0	0	0	0
HCO_3^-, mg/kg	427,00	323,80	327,00	389,00	357,00	427,00	421,00
Ca^{2+}, mg/kg	300,60	200,40	306,60	308,60	298,50	300,60	290,60
Mg^{2+}, mg/kg	182,30	121,50	180,00	169,30	179,60	182,30	187,30
Physically clay, %	47,00	45,00	49,00	48,00	49,00	45,00	48,00
Physically sand, %	53,00	55,00	55,00	58,00	54,00	56,00	52,00

The levels of carbonate (CO_3^{2-}) were negligible across all samples, while bicarbonate (HCO_3^-) levels ranged from 32380 mg/kg to 42700 mg/kg. These high bicarbonate levels can influence soil pH and nutrient availability. Calcium (Ca^{2+}) concentrations ranged from 20040 mg/kg to 30860 mg/kg, and magnesium (Mg^{2+}) concentrations ranged from 12150 mg/kg to 18730 mg/kg, indicating good soil structure and fertility.

The mechanical composition of the soil, which includes the proportion of sand, silt, and clay, revealed that the soils are predominantly sandy loam. Sand content ranged from 52% to 58%, and clay content ranged from 45% to 49%. This texture is favorable for agricultural practices as it ensures good drainage and root penetration while retaining sufficient moisture and nutrients.

The soil samples collected from around the qanat systems indicate favorable conditions for agriculture. The slightly alkaline pH levels and low salinity, as indicated by electrical conductivity, suggest that these soils are well-suited for a variety of crops. The high organic matter content reflects good soil fertility, which is essential for healthy plant growth and productivity.

Sulfate and nitrate levels are within acceptable ranges for agricultural soils, although continued monitoring is necessary to ensure that these levels do not rise to harmful concentrations. The negligible carbonate levels and high bicarbonate levels highlight the influence of qanat water on soil chemistry, potentially affecting soil pH and nutrient availability.

The mechanical composition of the soils, predominantly sandy loam, is ideal for agriculture as it provides good drainage, root penetration, and moisture retention capabilities. This balance of physical properties supports robust plant growth and helps prevent issues such as waterlogging and soil compaction (Glinski, 1990).

Implications for Agricultural Practices and Water Management

The analysis of water and soil samples from the qanat systems in the Cebrail district provides valuable insights into the suitability of these resources for sustainable agricultural practices. The generally high-quality water, with minimal contamination, supports the use of qanat systems for both drinking and irrigation purposes. However, the variations in mineral content and salinity among different qanat systems highlight the need for site-specific management practices to ensure optimal soil health and crop productivity.

The soil analysis indicates favorable conditions for agriculture, with good pH levels, organic matter content, and low salinization risk. The high bicarbonate levels and variations in sulfate and nitrate concentrations necessitate regular monitoring and potential amendments to maintain soil health and fertility.

The results of this study align with previous findings on qanat water quality. Studies in other regions of Azerbaijan, such as Nakhchivan, and in countries like Iran and Oman, have shown that qanat water often maintains high quality due to natural filtration through underground channels (Lightfoot, 1996; Hamidian et al., 2015). The slight variations in some parameters, such as higher mineral content in certain qanat systems, are consistent with the findings of Somaratne and Frizenschaf (2013), Baba and Gündüz (2017), and Abanyie et al. (2023) that local geology and aquifer composition can influence water quality.

The generally low levels of turbidity and absence of odor confirm the natural filtration efficiency of the qanat systems. The pH levels being within the ideal range for drinking and irrigation align with global observations of qanat water properties. The higher electrical conductivity and mineralization levels in some qanat systems indicate the need for careful water management, especially for irrigation purposes. This finding is supported by FAO guidelines (FAO, 1985) which emphasize monitoring and managing irrigation water with high EC to prevent soil salinization.

The calcium and magnesium concentrations, although high, are not uncommon in groundwater sources in arid and semi-arid regions. Effective treatment methods such as lime softening or ion exchange can make this water suitable for drinking. Sodium levels, while high for direct consumption, can be managed through blending with lower sodium water or using gypsum to ameliorate the effects on soil structure when used for irrigation. The variations in sulfate and chloride concentrations also necessitate monitoring, especially since they can affect soil and plant health over time. The low levels of ammonium, nitrate, nitrite, phosphate, fluoride, and cyanide in the water samples further confirm the suitability of qanat water for agricultural use, provided that appropriate management practices are employed.

Overall, the study underscores the importance of qanat systems in providing reliable water sources in arid and semi-arid regions. By integrating traditional water management practices with modern agricultural techniques, the sustainability and productivity of these systems can be enhanced, contributing to the socio-economic well-being of local communities. This comprehensive analysis of water and soil quality around qanat systems provides a solid foundation for sustainable agricultural practices and effective water resource management in the Karabakh region.

Relationship Between Water Quality and Soil Characteristics

The findings of this study highlight significant interactions between water quality and soil characteristics in the Cebrail district of the Karabakh region. The qanat systems, which provide a reliable source of water, directly influence the physicochemical properties of the surrounding soils. This relationship is crucial for understanding how to manage both water and soil resources sustainably, especially in the context of climate change.

The high mineralization levels and electrical conductivity (EC) of the water samples from certain qanat systems suggest that irrigation with this water can contribute to soil salinization if not managed properly. The elevated levels of calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^{+}) in the water are likely to affect soil structure and fertility. For instance, high sodium levels can lead to soil dispersion, reducing permeability and aeration, which negatively impacts plant growth.

Conversely, the relatively low levels of contaminants such as ammonium nitrogen (NH_4^{+}-N), nitrates (NO_3^{-}), and phosphates (PO_4^{3-}) in the water indicate that it can be beneficial for maintaining soil fertility without contributing significantly to nutrient runoff or groundwater pollution. The presence of essential nutrients in the water can enhance soil nutrient content, supporting sustainable agricultural productivity.

Recommendations for Sustainable Land and Water Resource Management

To mitigate the potential negative impacts of high mineral content in irrigation water, several management practices can be recommended:

- Regular Monitoring: Continuous monitoring of both water and soil quality is essential. This includes tracking salinity levels, pH, and concentrations of key ions in both water and soil to detect any adverse changes promptly.
- Blending Water Sources: Blending qanat water with lower salinity water can help reduce overall salinity levels, making it safer for both drinking and irrigation purposes. This approach can also balance out the mineral content.
- Soil Amendments: Applying soil amendments such as gypsum can help displace sodium ions from soil particles, improving soil structure and reducing the risk of sodicity. Organic matter additions can also enhance soil structure and nutrient-holding capacity.
- Irrigation Management: Implementing efficient irrigation techniques, such as drip irrigation, can minimize water usage and reduce the risk of soil salinization. Additionally, scheduling irrigation based on soil moisture content and crop needs can prevent over-irrigation and leaching of nutrients.
- Crop Selection: Choosing salt-tolerant crop varieties can help sustain agricultural productivity in areas with higher soil salinity. These crops can better withstand the stress caused by saline conditions.
- Integrated Water Resource Management: Developing a comprehensive water resource management plan that considers the variability of water quality across different qanat systems is crucial. This plan should integrate traditional knowledge with modern practices to enhance water use efficiency and sustainability.

Adaptation to Climate Change

As global temperatures rise and precipitation patterns become more unpredictable, the reliance on qanat systems as a sustainable water source becomes increasingly important. Ensuring the sustainability of these systems involves not only maintaining the quality of water but also protecting the surrounding soil environment.

- Climate-Resilient Infrastructure: Investing in the maintenance and restoration of qanat infrastructure to withstand extreme weather events is vital. This includes reinforcing tunnels and wells to prevent collapse and ensuring that water channels remain unblocked.
- Water Conservation Practices: Promoting water conservation techniques among local communities can help manage limited water resources more effectively. This includes rainwater harvesting and efficient water storage methods.
- Community Engagement: Engaging local communities in water management decisions ensures that traditional practices and local knowledge are incorporated into modern water management strategies. This participatory approach can enhance the resilience of the qanat systems to climate change.
- Research and Innovation: Encouraging ongoing research into the effects of climate change on water and soil resources in the Karabakh region can provide valuable insights. Innovations in water management and soil conservation techniques can be developed and adapted to local conditions.

By understanding and managing the relationship between water quality and soil characteristics, and by implementing adaptive strategies to address the impacts of climate change, the sustainability of qanat systems can be ensured. These efforts will support the long-term viability of agricultural practices and the socio-economic well-being of communities in the Karabakh region.

Conclusion

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

The soil samples collected from the vicinity of the qanat systems demonstrated favorable conditions for agriculture, including good pH levels, low salinity, and high organic matter content. The mechanical composition of the soils, predominantly sandy loam, supports robust agricultural productivity by providing good drainage, root penetration, and moisture retention.

Key findings from the study include:

- The water from qanat systems generally meets WHO guidelines (WHO (2017) for turbidity and pH, making it suitable for consumption and irrigation.
- Electrical conductivity and mineralization levels in some qanat systems exceed recommended limits for drinking water, necessitating treatment or blending with lower salinity water.
- The high levels of calcium, magnesium, and sodium in certain qanat systems require management practices such as soil amendments and efficient irrigation techniques to mitigate potential negative impacts on soil structure and crop health.
- The low levels of contaminants such as ammonium, nitrate, nitrite, phosphate, fluoride, and cyanide in the water samples confirm the suitability of qanat water for agricultural use.

The relationship between water quality and soil characteristics highlights the need for integrated water and soil management strategies to ensure sustainable agricultural practices. Regular monitoring of both water and soil quality, along with the implementation of site-specific management practices, can help maintain soil health and crop productivity.

In the context of climate change, the sustainability of qanat systems becomes increasingly important. Adaptive strategies, including climate-resilient infrastructure, water conservation practices, community engagement, and ongoing research, are essential to enhance the resilience of these traditional water management systems.

By integrating traditional qanat systems with modern agricultural practices, the sustainability and productivity of these systems can be enhanced, contributing to the socio-economic well-being of local communities in the Karabakh region. This study not only fills existing knowledge gaps but also provides practical recommendations for sustainable land and water resource management, supporting long-term environmental conservation and agricultural development goals.

Acknowledgement

This work was supported by the Azerbaijan Science Foundation (Grant No: AEF-MQM-QA-2-2023-3(45)-05/05/3-M-05). We would also like to extend our gratitude to the anonymous reviewers whose insightful comments and suggestions significantly contributed to the improvement of this manuscript.

References

Abadi, B., Sadeghfam, S., Ehsanitabar, A., Nadiri, A.A., 2023. Investigating socio-economic and hydrological sustainability of ancient Qanat water systems in arid regions of central Iran. *Groundwater for Sustainable Development* 23: 100988.

Abanyie, S.K., Apea, O.B., Abagale, S.A., Amuah, E.E.Y., Sunkari, E.D., 2023. Sources and factors influencing groundwater quality and associated health implications: A review. *Emerging Contaminants* 9(2): 100207.

Abbass, K., Qasim, M.Z., Song, H. Murshed, M., Mahmood, H., Younis, I., 2022. A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environmental Science and Pollution Research 29: 42539–42559.

Abudanh, F., Twaissi, S., 2010. Innovation or technology immigration? The qanat systems in the regions of Udhruh and Ma'an in southern Jordan. *Bulletin of the American Society of Overseas Research* 360: 67-87.

Baba, A., Gündüz, O., 2017. Effect of geogenic factors on water quality and ıts relation to human health around Mount Ida, Turkey. *Water* 9: 66.

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

Carter, M.R., Gregorich, E.G., 2008. Soil Sampling and Methods of Analysis. CRC Press, 1224p.

Chambers, P., 2019. Standard Methods for the Examination of Water and Wastewater. ED-Tech Press, 332p.

FAO, 1985. Water quality for agriculture. Irrigation and drainage paper No. 29. Food and Agriculture Organization of the United Nations, Rome. 174p. Available at [Access date: 04.02.2024]: https://www.fao.org/4/t0234e/t0234e00.htm

Glinski, J., 1990. Soil Physical Conditions and Plant Roots. CRC Press, 260p.

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

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

Hamidian, A., Ghorbani, M., Abdolshahnejad, M., Abdolshahnejad, A., 2015. Qanat traditional eco-technology for ırrigation and water management. *Agriculture and Agricultural Science Procedia* 4: 119-125.

Koren, H., Bisesi, M., 2003. Handbook of environmental health. CRC Press. 876p.

Lightfoot, D.R., 1996. Syrian qanat Romani: history, ecology, abandonment. *Journal of Arid Environments* 33(3): 321-336.

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

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

Page, A.L., Keeney, D.R., Baker, D.E., Miller, R.H., Ellis, Jr. R., Rhoades, J.D., 1982. Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties. American Society of Agronomy, Soil Science Society of America, Madison, Wisconsin, USA, 1159p.

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

Rice, E.W., Bridgewater, L., 2012. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, 712 p.

Shams, A., 1996. A rediscovered-new 'Qanat' system in the High Mountains of Sinai Peninsula, with Levantine reflections. *Journal of Arid Environments* 110: 69-74.

Somaratne, N., Frizenschaf, J., 2013. Geological control upon groundwater flow and major ion chemistry with influence on basin management in a Coastal Aquifer, South Australia. *Journal of Water Resource and Protection* 5: 1170-1177.

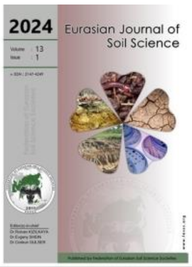
Telo da Gama, J., 2023. The role of soils in sustainability, climate change, and ecosystem services: challenges and opportunities. *Ecologies* 4(3): 552-567.

WHO, 2017. Guidelines for Drinking-water Quality, 4th Edition, incorporating the 1st addendum. World Health Organization, Geneva. 631p. Available at [Access date: 04.02.2024]: https://iris.who.int/bitstream/handle/10665/254637/9789241549950-eng.pdf?sequence=1

Eurasian Journal of Soil Science 2024, 13(4), 312 - 319

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



The role of zeolite and mineral fertilizers in enhancing Table Beet (*Beta vulgaris* L.) productivity in dark chestnut soils of Southeast Kazakhstan

Tursunay Vassilina [a], Beybit Nasiyev [b], Aigerim Shibikeyeva [a,*], Nurzikhan Seitkali [a], Samalbek Kossanov [c]

[a] Kazakh National Agrarian Research University, Almaty, Kazakhstan
[b] Zhangir Khan Agrarian Technical University, Uralsk, Kazakhstan
[c] Korkyt Ata Kyzylorda State University, Kyzylorda, Kazakhstan

Article Info
Received : 18.11.2023
Accepted : 01.07.2024
Available online: 05.07.2024

Author(s)
T.Vassilina
B.Nasiyev
A.Shibikeyeva *
N.Seitkali
S.Kossanov

* Corresponding author

Abstract

This study evaluated the effectiveness of zeolite, both alone and in combination with mineral fertilizers, in improving the yield and quality of table beets (Beta vulgaris L.) grown in dark chestnut soils of southeast Kazakhstan. The research was conducted at the Kazakh Research Institute of Horticulture during the 2022-2023 growing seasons using a randomized complete block design with six treatments: control (no fertilizers), zeolite 2 t/ha, N45P45K45 (single dose of mineral fertilizers), N90P90K90 (double dose of mineral fertilizers), zeolite 2 t/ha + N45P45K45, and zeolite 2 t/ha + N90P90K90, replicated three times. The application of zeolite significantly improved soil physical properties, such as water permeability and soil density, enhancing root development and water retention. Nutrient availability, particularly nitrate nitrogen and mobile phosphorus, increased significantly in zeolite-treated plots. The combination of zeolite and mineral fertilizers resulted in the highest improvements, with nitrate nitrogen content reaching 40.5 mg/kg and mobile phosphorus 89.2 mg/kg. Moreover, zeolite reduced heavy metal concentrations, particularly cadmium, by 50% compared to the control. Table beet yield significantly increased with zeolite application, with the highest yield of 62.7 t/ha achieved with 2 t/ha zeolite combined with double dose N90P90K90 fertilizers, compared to 42.8 t/ha in the control. Marketable yield also improved, indicating better crop quality. Nutrient composition of the beets improved, with increased dry matter content (21.9%) and reduced nitrate content (240 mg/kg) in zeolite-treated variants. In conclusion, zeolite, especially when combined with mineral fertilizers, effectively enhances soil health, nutrient availability, and table beet yield and quality.

Keywords: Zeolite, Table beet, dark chestnut soil, nutrient availability, sustainable agriculture.

Introduction

The agricultural sector is fundamental to the economy and food security of Kazakhstan, with vegetable crops playing a significant role (Suieubayeva et al., 2022). However, the excessive use of mineral fertilizers has led to soil degradation, nutrient imbalance, and environmental pollution (Krasilnikov et al., 2022). Mineral fertilizers can leach essential nutrients such as calcium, magnesium, and zinc from the soil, causing soil compaction and acidification. These issues negatively impact photosynthesis and plant resistance to diseases, ultimately reducing crop yields and quality. Furthermore, chemicals in fertilizers can enter the human food chain, posing health risks (Sathiyavani et al., 2017; Barłóg et al., 2022; Khan et al., 2022).

: https://doi.org/10.18393/ejss.1511141
: https://ejss.fesss.org/10.18393/ejss.1511141
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

The soils of southeast Kazakhstan, particularly dark chestnut soils, are crucial for agriculture due to their fertility (Maxotova et al., 2021; Zhaksybayeva et al., 2022). However, the productivity of these soils is threatened by unsustainable agricultural practices and climatic challenges. The region experiences a sharply continental climate with significant temperature fluctuations and irregular precipitation, which further exacerbates soil degradation issues(Saparov, 2014). Therefore, sustainable soil management practices are essential to maintain soil health and enhance crop productivity (Lal and Steward, 2013).

Organic fertilizers are often considered the best option for improving soil fertility and plant nutrition due to their balanced nutrient content. However, they can be expensive and not always available in sufficient quantities (Herencia et al., 2007; Baghdadi et al., 2018; Gamage et al., 2023). This has led to an increased interest in alternative soil amendments that can enhance soil properties and crop yields while being cost-effective and environmentally friendly (Sankar Ganesh et al., 2017; Snapp et al., 2023).

Zeolites, particularly clinoptilolite, have emerged as promising soil amendments (Garbowski et al., 2023). Zeolites are natural aluminosilicate minerals with high cation exchange capacities, allowing them to retain and gradually release essential nutrients such as potassium and ammonium (Cataldo et a., 2021; Li et al., 2013). This property makes them effective in improving soil fertility and plant growth. Additionally, zeolites can retain soil moisture, reducing the impact of drought and enhancing water use efficiency (Ippolito et al., 2011; Hazrati et al., 2017). Several studies (Mumpton, 1999; Ozbahce et al., 2015; Shivakumara et al., 2021) have shown that zeolites can significantly improve soil physical properties, nutrient availability, and crop yields. Ippolito et al. (2011) investigated the effects of combining clinoptilolite and urea on silt loam soil in maize (Zea mays L.) cultivation. They found that adding zeolite with urea enhanced the sorption of N-NH_4 and reduced its leaching. Clinoptilolite also increased the moisture content of sandy soil, resulting in higher maize yields with a zeolite application rate of 22 Mg ha^{-1} after six weeks. However, increasing the zeolite rate to 90 Mg ha^{-1} negatively impacted maize yield, likely due to the leaching of excessive Na+ ions from clinoptilolite, which raised soil salinity.

Kazakhstan has significant deposits of high-quality clinoptilolite, particularly in the Shankanay deposit. Despite its potential benefits, the use of natural clinoptilolite in agriculture has been limited (Sadenova et al., 2016; Vassilina et al., 2023). Recent research suggests that zeolite-enriched fertilizers can enhance the positive effects of natural zeolite, providing a controlled release of nutrients and improving soil health (Jarosz et al., 2022). This study aims to evaluate the effectiveness of zeolite, both alone and in combination with mineral fertilizers, in improving the yield and quality of table beets (Beta vulgaris L.) grown in dark chestnut soils of southeast Kazakhstan. The study focuses on assessing the impact of these treatments on soil physical and chemical properties, nutrient availability, and crop performance.

Material and Methods

Study Area

The research was conducted at the Kazakh Research Institute of Horticulture during the 2022-2023 growing seasons in the Almaty region of southeast Kazakhstan. The experimental site is characterized by dark chestnut soil, a crucial soil type in Kazakhstan that supports a significant portion of the country's agriculture. Dark chestnut soils are known for their fertility and ability to support a variety of crops. The mechanical composition of these soils includes a small amount of sand particles, with silt making up about 18.676% of the soil. The soil's pH is 8.36, with 2.27% humus content, 0.098% total nitrogen, 0.225% phosphorus, and 2.4% potassium.

The climate in the Almaty region is sharply continental, with significant temperature variations between summer and winter. Summers are warm, dry, and mostly clear, while winters are freezing, snowy, and partly cloudy. The average temperature in January is -7°C, and in July it is +28°C, with annual precipitation ranging from 350-600 mm. The growing season receives about 120-300 mm of this precipitation. The Köppen climate classification system classifies the area as warm continental, with mild winters and long, hot summers.

Experimental Design

The experiment was designed as a randomized complete block design with three replications. The experimental plots measured 63 m^2 each. The study included six treatments:

- Control (no fertilizers)
- Zeolite 2 t/ha
- N45P45K45 (single dose of mineral fertilizers)
- N90P90K90 (double dose of mineral fertilizers)

- Zeolite 2 t/ha + N45P45K45
- Zeolite 2 t/ha + N90P90K90

Soil and Fertilizer Application

Natural clinoptilolite zeolite from the Shankanay deposit was used. The chemical composition of the zeolite included 68.6% SiO_2, 18.5% Al_2O_3, 8.6% CaO, 2.2% MgO, and 1.5% Na_2O. Mineral fertilizers used were ammonium nitrate (34% N), ammophos (12% N, 52% P_2O_5), and potassium sulfate (50% K_2O). Zeolite and mineral fertilizers were applied manually in the fall of 2022 for plowing according to the experimental design.

Crop and Soil Management

The table beet variety 'Kyzylkonyr' was used as the test crop. Standard agronomic practices for the southeast Kazakhstan region were followed. Crops were planted in early spring and harvested manually at maturity. Zeolite was crushed to a particle size of less than 100 nm using a planetary ball mill. Soil and plant samples were analyzed using standardized methods to assess the effects of zeolite and mineral fertilizers on soil properties and table beet yield and quality.

Soil Analysis

Nitrate nitrogen (NO_3-N) content in the soil was measured using an ion-selective electrode method. Mobile phosphorus (P_2O_5) was determined using the Machigin method, which involves extraction with a sodium bicarbonate solution and subsequent colorimetric analysis. Water permeability was measured by applying a constant head of water to the soil surface and recording the infiltration rate over the first and second hours of the experiment. Soil density was determined by calculating the bulk density, which involves dividing the dry mass of soil by its volume (Page et al., 1982; Klute, 1986).

Plant Analysis

Dry matter content of the table beet samples was determined using the gravimetric method, which involves drying the samples at 105°C until a constant weight is achieved. Total sugar content was measured using the Bertrand method, a classical titration method for quantifying reducing sugars. Nitrate content in the table beet samples was determined potentiometrically using a nitrate ion-selective electrode (Kalra, 1997; Jones, 2001).

Statistical Analysis

Descriptive statistics, including means and standard deviations, were calculated for all measured parameters to provide an overview of the central tendency and variability of the data. Correlation and regression analyses were conducted to determine the relationships between soil nutrient levels, soil physical properties, and table beet yield. Pearson correlation coefficients were calculated to assess the strength and direction of the relationships between variables. Linear regression models were developed to predict table beet yield based on significant soil properties and nutrient levels. These analyses were performed using Microsoft Excel.

Results and Discussion

Soil Physical Properties

The application of zeolite significantly improved the physical properties of dark chestnut soil. As shown in Table 1, water permeability increased substantially in both the first and second hours of the experiment in the treated variants compared to the control. This indicates that zeolite treatments enhanced soil porosity and water infiltration, which are crucial for root development and plant growth. Moreover, the bulk density became more uniform, ranging from 1.18-1.20 g/cm^3 in zeolite-treated plots compared to the control.

Table 1. Effect of zeolite and mineral fertilizers on water permeability and bulk density

Treatment	Water Permeability (1st hour, mm/hr)	Water Permeability (2nd hour, mm/hr)	Bulk Density (g/cm^3)
Control (without fertilizers)	49.0	23.0	1.18
Zeolite 2 t/ha	86.5	62.8	1.20
N45P45K45	62.3	43.3	1.19
N90P90K90	60.9	40.9	1.19
Zeolite 2 t/ha + N45P45K45	87.2	68.5	1.20
Zeolite 2 t/ha + N90P90K90	89.2	65.1	1.20

The findings of this study align with previous research that underscores the benefits of using zeolite as a soil amendment. The improved soil physical properties, such as increased water permeability and more uniform soil density, support better root growth and nutrient uptake, leading to enhanced crop performance. These improvements in soil structure facilitate greater water retention and aeration, which are essential for healthy root development and efficient nutrient absorption. The results of this study are consistent with those of Al-Busaidi et al. (2008) and Ozbahce et al. (2015), who demonstrated that zeolite application significantly enhances soil physical properties, thereby improving overall soil quality and crop productivity. Karami et al. (2020) showed that the combination of nitrogen fertilization in the form of urea and zeolite significantly increased the water use efficiency in Amaranthus cultivation.

This enhanced water permeability and uniform soil density indicate that zeolite effectively modifies the soil structure, making it more conducive to plant growth. The increased porosity allows for better root penetration and water movement within the soil profile, which is critical for maintaining adequate soil moisture levels and preventing waterlogging. Additionally, the improved bulk density suggests that zeolite helps to create a more stable soil structure, reducing compaction and promoting healthier root systems. By improving these physical properties, zeolite not only enhances the immediate growing conditions for crops but also contributes to long-term soil quality and sustainability. These benefits make zeolite a valuable tool for sustainable agriculture, particularly in regions with poor soil structure or limited water availability.

Nutrient Availability

The addition of zeolite and mineral fertilizers significantly enhanced the availability of essential nutrients in the soil. Table 2 shows that nitrate nitrogen levels increased substantially in all treated variants compared to the control, especially during the germination period. The highest nitrate nitrogen content was observed in the zeolite 2 t/ha + N90P90K90 treatment, indicating improved nitrogen retention and gradual release. Similarly, mobile phosphorus levels increased significantly, particularly in treatments combining zeolite and mineral fertilizers.

Table 2. Impact of zeolite and mineral fertilizers on nitrate nitrogen and mobile phosphorus levels in soil

Treatment	Nitrate Nitrogen (mg/kg)	Mobile Phosphorus (mg/kg)
Control	10.0	31.3
Zeolite 2 t/ha	20.5	45.6
N45P45K45	25.8	50.7
N90P90K90	30.1	55.8
Zeolite 2 t/ha + N45P45K45	35.2	70.7
Zeolite 2 t/ha + N90P90K90	40.5	89.2

The increased availability of essential nutrients, particularly nitrate nitrogen and mobile phosphorus, is crucial for the growth and development of table beets. Zeolite's ability to retain and gradually release these nutrients ensures a steady supply throughout the growing season, which is critical for maximizing yield. This finding is supported by Filcheva and Tsadilas (2002), who noted that nutrient retention and availability are key factors in improving crop productivity.

The enhanced nutrient availability observed in this study can be attributed to the unique properties of zeolite. Zeolite's high cation-exchange capacity allows it to adsorb and retain significant amounts of essential nutrients, such as nitrogen and phosphorus, preventing their leaching from the soil. This property ensures that nutrients remain available to plants over an extended period, promoting sustained growth and higher yields.

The substantial increase in nitrate nitrogen levels, particularly in the zeolite 2 t/ha + N90P90K90 treatment, highlights the effectiveness of zeolite in improving nitrogen use efficiency. Nitrogen is a critical nutrient for plant growth, influencing various physiological processes, including chlorophyll synthesis and photosynthesis. By retaining nitrogen in the soil and releasing it gradually, zeolite helps maintain an optimal nitrogen supply, reducing the need for frequent fertilization and minimizing environmental impacts associated with nitrogen leaching. Similarly, the significant increase in mobile phosphorus levels in zeolite-treated soils underscores the importance of phosphorus in root development and energy transfer within plants. Phosphorus is essential for the formation of ATP, which powers various cellular activities. The enhanced availability of phosphorus in the zeolite-treated variants likely contributed to better root growth and overall plant vigor, leading to increased yields. These findings align with previous research by Aainaa et al. (2006) and Mondal et al (2021), who demonstrated that zeolite's ability to retain and slowly release nutrients can significantly improve nutrient use efficiency and crop performance. By enhancing nutrient availability, zeolite not only supports immediate plant growth but also contributes to long-term soil fertility and sustainability.

Table Beet Yield

The application of zeolite and mineral fertilizers had a significant impact on the yield of table beet. The yield data presented in Table 3 demonstrate the positive effects of these treatments on crop productivity. The combined application of zeolite and fertilizers resulted in the highest yield increases.

Table 3. Yield and marketable yield of table beets under different treatments

Treatment	Yield (t/ha)	Marketable Yield (%)
Control	42.8	85.0
Zeolite 2 t/ha	47.2	87.5
N45P45K45	50.3	89.0
N90P90K90	55.8	91.0
Zeolite 2 t/ha + N45P45K45	58.5	92.0
Zeolite 2 t/ha + N90P90K90	62.7	93.5

The yield increase ranged from 4.4 t/ha in the zeolite 2 t/ha treatment to 19.9 t/ha in the zeolite 2 t/ha + N90P90K90 treatment. Marketable yield also improved across all treatments, indicating the positive impact of zeolite and fertilizers on crop quality. These results are consistent with findings by Mumpton (1999), Ippolito et al. (2011), Ozbahce et al. (2015) and Shivakumara et al. (2021), who observed that zeolite application enhances crop yield by improving nutrient availability and soil physical properties. The significant increase in table beet yield and improvement in nutrient availability demonstrate the effectiveness of zeolite as a soil amendment. The combination of zeolite and mineral fertilizers resulted in the highest yield and quality improvements, confirming the synergistic effect of these treatments. Similar findings have been reported by several studies, indicating that zeolite enhances the efficiency of fertilizers, leading to better crop performance (Jarosz et al., 2022).

The significant increase in table beet yield and improvement in nutrient composition demonstrate the effectiveness of zeolite as a soil amendment. The combination of zeolite and mineral fertilizers resulted in the highest yield and quality improvements, confirming the synergistic effect of these treatments. Similar findings have been reported by several studies, indicating that zeolite enhances the efficiency of fertilizers, leading to better crop performance. The application of zeolite in maize cultivation was reported by Malekian et al. (2011) who opined that maize plants resulted in better response to zeolite when used as a fertilizer carrier at the rate of 60 g kg−1 of soil. The application of clinoptilolite zeolite (CZ) with a 75% recommended dose of fertilizer resulted in significantly similar cobs yield in maize as compared to the full recommended dose of fertilizer (Aainaa et al., 2018). The observed yield increases can be attributed to several factors. Zeolite's cation-exchange capacity improves the retention and availability of essential nutrients like nitrogen, phosphorus, and potassium. This ensures a steady supply of nutrients to the plants throughout the growing season, promoting better growth and higher yields. The highest yields were recorded in treatments combining zeolite with N90P90K90, highlighting the synergistic effect of zeolite and higher doses of mineral fertilizers.

In terms of marketable yield, all treatments showed improvements over the control, with the most significant gains seen in the combined treatments of zeolite and fertilizers. This suggests that not only does zeolite improve overall yield, but it also enhances the quality of the produce, making it more marketable. The application of zeolite also contributed to a reduction in nitrate content in the table beet, indicating a safer and more nutritious product. The nitrate content decreased from 350 mg/kg in the control to 240 mg/kg in the zeolite 2 t/ha + N90P90K90 treatment (Table 4). This reduction in nitrate content is crucial as high nitrate levels in vegetables can pose health risks to consumers. Lower nitrate levels in the produce indicate a healthier and safer food product, aligning with consumer demand for higher-quality and safer food options.

Table 4. Nitrate Content, total sugar and dry matter of table beets treated with zeolite and mineral fertilizers

Treatment	Dry Matter (%)	Total Sugar (%)	Nitrate Content (mg/kg)
Control	19.5	8.5	350
Zeolite 2 t/ha	20.1	8.3	320
N45P45K45	20.5	8.2	300
N90P90K90	21.0	8.0	280
Zeolite 2 t/ha + N45P45K45	21.5	7.8	260
Zeolite 2 t/ha + N90P90K90	21.9	7.5	240

Correlation and Regression Analysis

Statistical analysis revealed strong correlations between nutrient availability in the soil and table beet yield. Pearson correlation coefficients were calculated to assess the strength and direction of the relationships between variables. A positive correlation ($r = 0.99$) was found between nitrate nitrogen content during the germination period and yield. Similarly, mobile phosphorus showed a significant correlation with yield ($r = 0.94$). These relationships highlight the importance of balanced nutrient management in optimizing crop production.

Linear regression models were developed to predict table beet yield based on significant soil properties and nutrient levels, with equations established to describe these relationships. The following regression equations were determined:

Nitrate Nitrogen and Yield:

$$y=167x_1-0.41x_2-0.29x_3-2.15$$

y: Yield (t/ha)
x1,x2,x3: Nitrate nitrogen content in the 0-20 cm soil layer during the periods of germination, bunching, and technical ripeness (mg/kg of soil).
Correlation coefficient $r=0.99$, $r^2=0.98$

Mobile Phosphorus and Yield:

$$y=130x_2+2.17x_3-167x_1-12.9$$

y: Yield of table beet (t/ha)
x1,x2,x3: Mobile phosphorus content in the 0-20 cm soil layer during the periods of germination, bunching, and technical ripeness (mg/kg of soil).
Correlation coefficient $r=0.94$, $r^2=0.88$

The results from the correlation and regression analysis underscore the critical role of nutrient availability in determining table beet yield. The strong positive correlation between nitrate nitrogen content and yield ($r = 0.99$) highlights nitrogen's essential role in promoting vegetative growth and enhancing overall productivity. This finding is consistent with previous research that has demonstrated the importance of nitrogen in supporting plant growth and maximizing yield (Ippolito et al., 2021). The significant correlation between mobile phosphorus and yield ($r = 0.94$) further emphasizes the importance of phosphorus in root development and energy transfer processes within the plant. Adequate phosphorus availability is crucial during key growth stages to ensure robust root systems and efficient nutrient uptake, ultimately leading to higher yields. The high coefficients of determination (r^2) for the regression models indicate that nitrate nitrogen and mobile phosphorus levels are strong predictors of table beet yield. The regression equations provide valuable insights for developing fertilization strategies that optimize nutrient availability at critical growth stages. For instance, ensuring sufficient nitrate nitrogen during germination and bunching periods can significantly enhance yield, as reflected in the regression model with an r^2 value of 0.98. Similarly, managing mobile phosphorus levels to maintain adequate supply during the technical ripeness stage is vital for maximizing yield potential, as indicated by the regression model with an r^2 value of 0.88. These models demonstrate the significant predictive power of nutrient levels for table beet yield, underscoring the critical role of effective fertilization strategies in achieving high productivity. The strong correlations and high coefficients of determination (r^2) indicate that the regression models accurately represent the relationships between soil nutrients and crop yield. These findings provide a robust framework for optimizing nutrient management practices to enhance table beet productivity, ultimately contributing to sustainable agricultural production systems.

Conclusion

The study demonstrates the significant impact of zeolite and mineral fertilizers on the physical and chemical properties of dark chestnut soil, nutrient availability, and the yield and quality of table beets. The application of zeolite significantly improved soil physical properties, such as water permeability and soil density, which are crucial for root development and plant growth. The enhanced soil structure facilitated better water infiltration and retention, supporting healthier root systems and efficient nutrient uptake. The addition of zeolite and mineral fertilizers notably increased the availability of essential nutrients, particularly nitrate nitrogen and mobile phosphorus. This improved nutrient retention and gradual release ensured a steady supply of nutrients throughout the growing season, leading to higher crop yields. The highest yield increases were observed in treatments combining zeolite with higher doses of mineral fertilizers, highlighting the synergistic effects of these amendments. The correlation and regression analyses revealed strong positive correlations between nutrient availability and table beet yield. The regression models demonstrated the predictive power of nitrate nitrogen and mobile phosphorus levels on crop productivity, emphasizing the critical role of balanced nutrient management in optimizing yield.

Overall, the findings underscore the effectiveness of zeolite as a soil amendment in enhancing soil health, nutrient availability, and crop performance. The combination of zeolite and mineral fertilizers not only improved yield and marketable quality but also reduced nitrate content in table beets, producing a safer and more nutritious product. These results suggest that the use of zeolite in sustainable agricultural practices can contribute to improved crop productivity and food quality. Future research should focus on the long-term effects of zeolite application on soil health and crop performance under various environmental conditions. Additionally, exploring the optimal application rates and methods for different crops and soil types will further validate the benefits of zeolite and enhance its practical implementation in agriculture.

Acknowledgement

This research was supported by the Ministry of Education and Science of the Republic of Kazakhstan under the research grant “AP13068349 Development of methods for increasing the productivity of vegetable crops by using nanomodified zeolite fertilizer in the southeast of Kazakhstan”. The authors also wish to thank the anonymous reviewers for their valuable comments and suggestions which helped to improve the quality of this manuscript.

References

Aainaa, H.N., Haruna Ahmed, O., Ab Majid, N.M., Reinhart, K.O., 2018. Effects of clinoptilolite zeolite on phosphorus dynamics and yield of Zea mays L. cultivated on an acid soil. *PLoS ONE* 13 (9): e0204401.

Al-Busaidi, A. Yamamoto, T. Inoue, M. Eneji, A.E. Mori, Y. Irshad, M., 2008. Effects of zeolite on soil nutrients and growth of barley following irrigation with saline water. *Journal of Plant Nutrition* 31(7): 1159-1173.

Baghdadi, A., Halim, R.A., Ghasemzadeh, A., Ramlan, M.F., Sakimin, S.Z., 2018. Impact of organic and inorganic fertilizers on the yield and quality of silage corn intercropped with soybean. *Peer J* 6: e5280.

Barłóg, P., Grzebisz, W., Łukowiak, R., 2022. Fertilizers and fertilization strategies mitigating soil factors constraining efficiency of nitrogen in plant production. *Plants* 11(14): 1855.

Cataldo, E., Salvi, L., Paoli, F., Fucile, M., Masciandaro, G., Manzi, D., Masini, C.M., Mattii, G.B., 2021. Application of zeolites in agriculture and other potential uses: A review. *Agronomy* 11(8): 1547.

Filcheva, E.G., Tsadilas, C.D., 2002.Influence of clinoptilolite and compost on soil properties. *Communications in Soil Science and Plant Analysis* 33 (3-4): 595-607.

Gamage, A., Gangahagedara, R., Gamage, J., Jayasinghe, N., Kodikara, N., Suraweera, P., Merah, O., 2023. Role of organic farming for achieving sustainability in agriculture. *Farming System* 1(1): 100005.

Garbowski, T., Bar-Michalczyk, D., Charazińska, S., Grabowska-Polanowska, B., Kowalczyk, A., Lochyński, P., 2023. An overview of natural soil amendments in agriculture. *Soil and Tillage Research* 225: 105462.

Hazrati, S., Tahmasebi-Sarvestani, Z., Mokhtassi-Bidgoli, A., Modarres-Sanavy, S.A.M., Mohammadi, H., Nicola,S., 2017. Effects of zeolite and water stress on growth, yield and chemical compositions of Aloe vera L. *Agricultural Water Management* 181: 66-72.

Herencia, J.F., Ruiz-Porras, J.C., Melero, S., Garcia-Galavis, P.A., Morillo, E., Maqueda, C., 2007. Comparison between organic and mineral fertilization for soil fertility levels, crop macronutrient concentrations, and yield. *Agronomy Journal* 99(4): 973-983.

Ippolito, J.A., Tarkalson, D.D., Lehrsch, G.A., 2011. Zeolite soil application method affects inorganic nitrogen, moisture, and corn growth. *Soil Science* 176(3):136-142.

Jarosz, R., Szerement, J., Gondek, K., Mierzwa-Hersztek, M., 2022. The use of zeolites as an addition to fertilisers – A review. *Catena* 213: 106125.

Jones, J.B., 2001. Laboratory guide for conducting soil tests and plant analyses. CRC Press, New York, USA. 363p.

Kalra, Y.P., 1997. Handbook of Reference Methods for Plant Analysis. CRC Press, 320p.

Karami, S., Hadi, H., Tajbaksh, M., Modarres-Sanavy, S.A.M., 2020. Effect of zeolite on nitrogen use efficiency and physiological and biomass traits of Amaranth (Amaranthus hypochondriacus) under water-deficit stress conditions. *Journal of Soil Science and Plant Nutrition* 20(3): 1427-1441.

Khan, M., Arif, M., Karim, T., Khan , D., Rashid, H., Ahmad, F., Zeeshan, M., 2022. Food safety and the effect of fertilizers on human health. *International Journal of Endorsing Health Science Research* 11(1): 54–57.

Klute, A.. 1986. Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, Second Edition. (Ed.). ASA-SSSA, Madison, Wisconsin, USA. 1188p.

Krasilnikov, P., Taboada, M.A., Amanullah, 2022. Fertilizer use, soil health and agricultural sustainability. *Agriculture* 12(4): 462.

Lal, R., Steward, B.A., 2013. Principles of sustainable soil management in agroecosystems. CRC Press. 552p.

Li, Z., Zhang, Y., Li, Y., 2013. Zeolite as slow release fertilizer on spinach yields and quality in a greenhouse test. *Journal of Plant Nutrition* 36(10): 1496-1505.

Malekian, R., Abedi-Koupai, J., Eslamian, S.S., 2011. Influences of clinoptilolite and surfactantmodified clinoptilolite zeolite on nitrate leaching and plant growth. *Journal of Hazardous Materials* 185: 970–976.

Maxotova, A., Nurbayeva, E., Aitbayev, T., Nurgaliyeva, B., 2021. Yield and yield components of five tomato varieties (Solanum lycopersicum) as influenced by chemical NPK fertilizer applications under chestnut soil conditions. *Eurasian Journal of Soil Science* 10(4): 327 - 331.

Mondal, M., Biswas, B., Garai, S., Sarkar, S., Banerjee, H., Brahmachari, K., Bandyopadhyay, P.K., Maitra, S., Brestic, M., Skalicky, M., Ondrisik, P., Hossain, A., 2021. Zeolites enhance soil health, crop productivity and environmental safety. *Agronomy* 11(3): 448.

Mumpton, F.A., 1999. La Roca Magica: Uses of natural zeolites in agriculture and industry. *Proceedings of the National Academy of Sciences (PNAS)* 96: 3463–3470.

Ozbahce, A., Tari, A.F., Gönülal, E., Simsekli, N., Padem, H., 2015. The effect of zeolite applications on yield components and nutrient uptake of common bean under water stress, *Archives of Agronomy and Soil Science* 61(5): 615-626.

Page, A.L., Keeney, D. R., Baker, D.E., Miller, R.H., Ellis, R. Jr., Rhoades, J.D., 1982. Methods of soil analysis, Part 2 - Chemical and Microbiological Properties. ASA-SSSA, Madison, Wisconsin, USA. 1159p.

Sadenova, M.A., Abdulina, S.A., Tungatarova, S.A., 2016. The use of natural Kazakhstan zeolites for the development of gas purification catalysts. *Clean Technologies and Environmental Policy* 18: 449–459.

Sankar Ganesh, K., Sundaramoorthy, P., Nagarajan, M., Lawrence Xavier, R., 2017. Role of organic amendments in sustainable agriculture. In: Sustainable Agriculture towards Food Security. Dhanarajan, A. (Ed.). Springer, Singapore. pp 111–124.

Saparov, A., 2014. Soil resources of the Republic of Kazakhstan: Current status, problems and solutions. In: Novel Measurement and Assessment Tools for Monitoring and Management of Land and Water Resources in Agricultural Landscapes of Central Asia. Mueller, L., Saparov, A., Lischeid, G. (Eds.), Environmental Science and Engineering, Springer International Publishing, Switzerland, pp. 61-73.

Sathiyavani, E., Prabaharan N.K., Krishna Surendar, K., 2017. Role of mineral nutrition on root growth of crop plants – A review. *International Journal of Current Microbiology and Applied Sciences* 6(4): 2810-2837.

Shivakumara, M.N., Krishna Murthy, R., Jagadeesha, G.S., 2021. Influence of zeolite application on growth, yield and yield attributes of finger millet (Eleusine Coracana L.) in rainfed condition. *International Journal of Plant and Soil Science* 33(24): 43-58.

Snapp, S., Sapkota, T.B., Chamberlin, J., Cox, C.M., Gameda, S., Jat, M.L., Marenya, P., Mottaleb, K.A., Negra, C., Senthilkumar, K., Sida, T.S., Singh, U., Stewart, Z.P., Tesfaye, K., Govaerts, B., 2023.Spatially differentiated nitrogen supply is key in a global food–fertilizer price crisis. *Nature Sustainability* 6: 1268–1278.

Suieubayeva, S., Denissova, O., Kabdulsharipova, A., Idikut Ozpence, A., 2022. The agricultural sector in the Republic of Kazakhstan: Analysis of the state, problems and ways of solution. *Eurasian Journal of Economic and Business Studies* 66(4): 19–31.

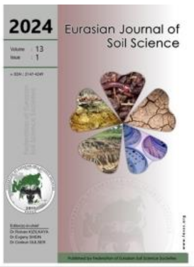
Vassilina, T., Nasiyev, B., Rvaidarova, G., Shibikeyeva, A., Seitkali, N., Salykova, A., Yertayeva, Z., 2023. The effects of clinoptilolite type of zeolite and synthesised zeolite-enriched fertilizer on yield parameters of Cucumber (Cucumis sativus) plant and some chemical properties in dark chestnut soil. *Eurasian Journal of Soil Science* 12(3): 277-281.

Zhaksybayeva, G., Balgabayev, A., Vassilina, T., Shibikeyeva, A., Malimbayeva, A., 2022. Yield of sugar beet and changes in phosphorus fractions in relation to long term P fertilization in chestnut soil of Kazakhstan. *Eurasian Journal of Soil Science* 11(1): 25-32.

Eurasian Journal of Soil Science 2024, 13(4), 320 - 327

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



Effect of potassium application on maize to sandy soil under deficit irrigation conditions

Munir J. Rusan [a,*], **Ayat Al-Masri** [a], **Rashid Lubani** [b]

[a] Department of Natural Resources and Environment, Jordan University of Science and Technology, Irbid, Jordan
[b] Arab Potash Company. Amman, Jordan

Article Info
Received : 30.03.2024
Accepted : 19.07.2024
Available online: 22.07.2024

Author(s)
M.J.Rusan *
A. Al-Masri
R.Lubani

* Corresponding author

Abstract

Maize is widely growth in arid and semi-arid region where, drought is common and a limiting factor for crop production. Potassium plays a key role in enhancing plant growth under drought condition. The objective of this study is to determine the effect of K fertilization with and without NP on maize growth grown in sandy loam soil under adequate and deficit irrigation conditions. The following treatments were investigated in pot experiment: (1) control with no fertilizer application (C); (2) 128 kg N + 328 kg P_2O_5 ha^{-1} (NPK0); (3) 128 kg N + 328 kg P_2O_5 ha^{-1} + 152.5 kg K_2O ha^{1} (NPK1); (4) 128 kg N + 328 kg P_2O_5 ha^{-1} + 305 kg K_2O ha^{-1} (NPK2); and 128 kg N + 328 kg P_2O_5 ha^{-1} + 457.5 kg K_2O ha^{-1} (NPK3). Treatments were investigated under adequate and deficit soil moisture content. Each pot filled with 3.5 kg air-dry soil and seeded with maize and pots were watered according to the treatments. The results indicated that plant growth and nutrient uptake were significantly reduced under water stress condition. The application of NP increased plant growth and nutrient uptake and further were increased with K application. K application also enhanced plant tolerance to deficit soil moisture condition. In addition, K enhanced nutrient uptake and leaf chlorophyll content. Based on the results, it can be concluded that application of NP for maize was not adequate to achieve the highest plant growth, unless it is combined with K application. In addition, K application enhances plant tolerance to water stress.

Keywords: Maize, K fertilization, water stress, sandy soil.

Introduction

Maize (*Zea mays* L.), a crop of worldwide distribution, is an important cereal crop for human food and livestock feed consumption as well as for food industry owing to its high nutritional value (Ali et al., 2016). Maize is grown considerably in arid and semi-arid regions where drought is common and one of the most limiting factors for maize production in this region (FAO, 1999; Hammad and Ali, 2014). The impact of drought became even more sever due to prevailing climate change (Song et al., 2010) and several researchers predicted the climate change enhanced drought will be more severe in term of intensity and duration in several parts of the world (Liu et al., 2020; Qing et al., 2022; Kang et al., 2022).

Although maize as a C4 crop is relatively an efficient water user but is negatively affected by soil moisture deficit during vegetative and reproductive growth stages (Aslam et al., 2015; Vennam et al., 2023). Among cereal crops, Gopalakrishna et al. (2023) considered maize as the most susceptible to drought. Researchers reported a significant reduction in photosynthetic rate and maize grain quality (Yousaf et al., 2023). Moreover, maize has a relatively high nutrients requirement and besides water soil fertility level is considered another limiting factor for maize production. Therefore, growers should grow maize in a soil with high soil fertility level with balanced supply of all essential plant nutrients (Khalid and Shedeed, 2015).

: https://doi.org/10.18393/ejss.1520108
: https://ejss.fesss.org/10.18393/ejss.1520108
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

Potassium is an essential plant nutrient for plant growth and development (Caliskan and Caliskan, 2018). K is of particular importance when maize is growing in arid and semi-arid region because K play a key role in increasing water use efficiency and enhancing crops tolerance to drought stress (Rengel and Damon, 2008; Khalid and Shedeed, 2015). Adequate supply of K to crops, not only increases the quantity and quality of yields of cereal crops but also enhances their tolerance to biotic and abiotic stresses (Pettigrew, 2008; Zorb et. al., 2014). K enhances tolerance to water stress through enhancing root growth during early growth stages which lead to enhancing water and nutrient uptake and consequently support plant survival during stress condition (Hammer et al., 2009; Vennam et al., 2023). K plays a key role in enhancing water use efficiency and crop tolerance to drought stress through its role in stomatal regulation (Studer et al., 2017). Under soil moisture stress conditions, adequate supply of K enhances root growth, which consequently enhances plants water uptake and improved crop yield (Römheld and Kirkby, 2010; Hassan et al., 2017).

Most crops, including maize, require as high amount of K as N and excluding K from long term fertilization, especially under intensive cultivation, will lead to soil K depletion (Majumdar et al., 2021; Das et al., 2019, 2020, 2022). Neglecting, K fertilization will eventually threaten crop production, soil health, agricultural sustainability and global food security (Regmi et al., 2002; Cakmak, 2010; Lu et al., 2017; Brownlie et al., 2024).

The impact of both deficit irrigation and low soil fertility levels is worsened and exacerbated by fertilizer mismanagement practices. Adopting fertilizer best management practices is vital for improving growth and production of crops under various farming system (Hasanuzzaman et al., 2018). On the other hand, farmers are traditionally and commonly have been applying only N and P for a long period of time, which led to soil K depletion and soil nutrient imbalance with respect to K (Brownlie et al., 2024). Therefore, the hypothesis of this study is that the application of potassium to potassium-depleted sandy soil will improve plant growth deficit irrigation. The main objective of this study was to determine the effect of application of different K rates on growth and nutrient uptake of maize grown in sandy soil under adequate and deficit irrigation conditions.

Material and Methods

A greenhouse pot experiment was conducted to determine the effect of potassium rate on the nutrient uptake and growth of maize grown in sandy loam soil under adequate and deficit soil moisture conditions. The soil used in the experiment was collected from agriculture fields from the top 30 cm from eastern part of Jordan (Mafraq Governorate), where coarse textured soils are common. The soil was air-dried and sieved through a 5 mm sieve. The soil was analyzed for texture by hydrometer method (Gee and Bauder, 1986); soil pH and soil EC were measured on 1:1 soil : water suspension (McLean, 1982 and Rhoades, 1982, respectively); total N by Kjeldahl (Nelson and Sommers, 1980); available P by extraction with sodium bicarbonate (Olsen et al., 1954); exchangeable K, Ca and Mg by extraction with 1 M NH_4OAc (Thomas, 1982); cation exchange capacity (CEC) by the method of Palemio and Rhoades (1977). The major soil characteristics are presented in Table 1.

Table 1. Soil characteristics before conducting the experiment.

Soil pH	8.10
Soil EC, dS m^{-1}	0.75
CEC, Cmolc kg^{-1} soil	7,21
Soil N, %	0.04
Soil P, mg kg^{-1}	10.34
Soil K, mg kg^{-1}	208
Ca, %	13.11
Na, %	3.22
Soil Texture	Sandy loam

The following treatments (Table 2) were investigated in a randomized Complete Block Design (RCBD) with four replication and a total of 40 experimental units.

Each pot was filled with 3.5 kg air-dried soil. According to the treatment, N and P were added to each pot as di-ammonium phosphate while potassium as potassium sulfate. Four maize seeds per pot were seeded. After germination three homogeneous plants were kept per pot. Pots were watered periodically according to the treatments and the soil moisture was kept at 100% and to 50% of the field capacity during the period of the experiment. 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% and 50% of field capacity.

Table 2. Treatments' structure

Two Soil moisture levels (Main plot):	-
100% Field Capacity water content (Adequate)	100%-FC
50% Field Capacity water content (Deficit)	50%-FC
Five Fertilizer application treatments (Sub plot)*:	-
No fertilizer application	C
128 kg N + 328 kg P_2O_5 + 000 kg K_2O ha^{-1}	NPK0
128 kg N + 328 kg P_2O_5 + 152.5 kg K_2O ha^{-1}	NPK1
128 kg N + 328 kg P_2O_5 + 305 kg K_2O ha^{-1}	NPK2
128 kg N + 328 kg P_2O_5 + 457.5 kg K_2O ha^{-1}	NPK3

*N and P were applied as Diammonium phosphate (DAP) and the recommended rate of 70-80 kg DAP ha^{-1} (Athamenh et al., 2015) K as potassium sulfate

At the end of the growing period and immediately before harvest leaf Chlorophyll content was measured using Chlorophyll Content Meter (CCM-300) device (Gitelson et al., 1999). The whole plants were harvested, and the fresh weight was recorded, then oven-dried at 70°C and oven dry weight was recorded. Oven dried plants were ground to a fine powder using a laboratory mill with 0.5 mm sieve. The milled plant samples were analyzed for total N using a modified micro-Kjeldahl digestion procedure (Bremner and Mulvaney, 1982). Total P and K were determined in the dry ash digestion. P was determined using Vanadate–Molybdate–Yellow method, K by flame photometry (Chapman and Pratt, 1961). Representative soil sample was also taken from each pot after thoroughly mixing the soil. Soil samples were 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 analyzed all data collected from this search with SAS version 9.0 (2002) software. Means were subjected to analysis of variance (ANOVA) at five percent level of significance ($P \leq 0.05$). Means separation was performed according to Least Significant Difference LSD method at $P \geq 0.05$.

Results and Discussion

Treatments effect on shoot dry weight of maize is shown in Figure 1. Shoot dry weight was the lowest for the control treatment, where fertilizers were not added, under both adequate (100%-FC) and deficit (50%-FC) soil moisture contents. For all treatments, the shoot dry weight was significantly lower under 50%-FC moisture content. Application of NP fertilizers significantly increased dry weigh compared to the control. However combined application of K with NP resulted in further increase in dry weight, and the highest shoot dry weight was obtained with the highest K rates (NPK2 and NPK3) under adequate soil moisture content. Under water deficit condition however, the shoot dry weight increased similarly by all rates of K application. The application of NP was not adequate to get the highest plant growth, unless K is applied with NP, suggesting that both water deficit and poor soil fertility levels are the two limiting factors of maize growth under the conditions of this study. This result agrees with the findings of other researchers who reported reduction in maize growth under water deficit condition and poor soil fertility (Wang et al., 2013; Hammad and Ali, 2014; Amanullah et al., 2016; Vennam et al., 2023; Yousaf et al., 2023).

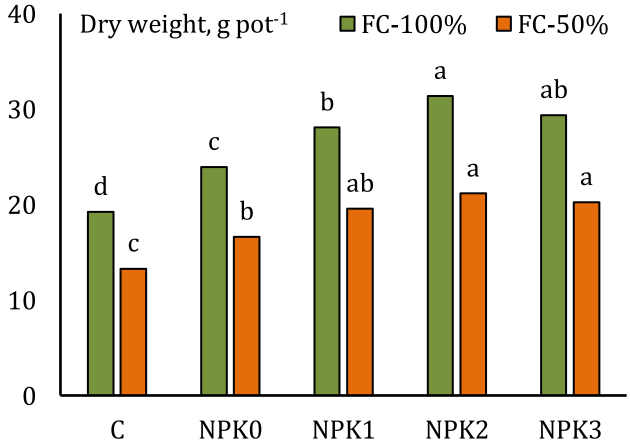


Figure 1. Shoot Dry weight of maize as affected by K application rate under two field capacity (FC) water contents. Columns with similar letters are not significantly different at $P \leq 0.05$.

Treatments effect on N uptake and chlorophyll content are shown in Figure 2 and Figure 3, receptively. Under both adequate and deficit irrigation contents, N uptake was the lowest for the control treatment and increased significantly by NP application. Combining the highest two rates of K (NPK2 and NPK3) with NP application resulted in further increase in N uptake.

Enhancing N use efficacy by K application was also found by other researchers (Rutkowska et al., 2014). Leaf chlorophyll content was the lowest for the control treatment and under deficit irrigation contents for all treatments. Compared to the control, addition of NPK0 increased the leaf chlorophyll content. The highest two rates of K (NPK2 and NPK3) increased the leaf chlorophyll content further under both soil moisture contents. It has been documented that plants grown under water stress condition had lower chlorophyll content (Efeoğlu et al., 2009; Asgharipour and Heidari, 2011; Xiang et al., 2013; Karimpour, 2019; Wach and Skowron, 2022), but upon application of K to these plants enhanced their tolerance to water stress and their chlorophyl content significantly increased (Siddiqui et al., 2012; Talal et al., 2015).

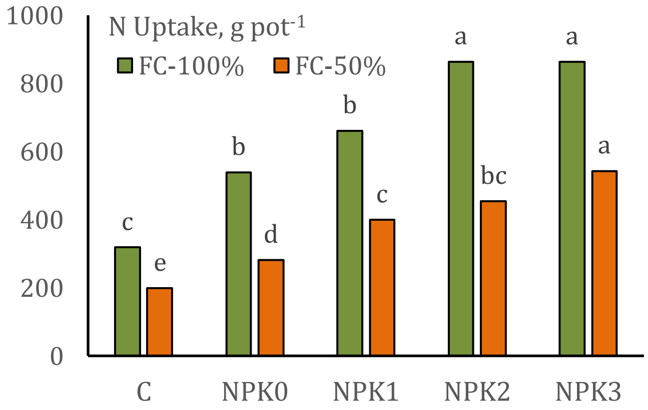


Figure 2. N uptake by maize as affected by K application rate under two field capacity (FC) water contents. Columns with similar letters are not significantly different at P≤0.05.

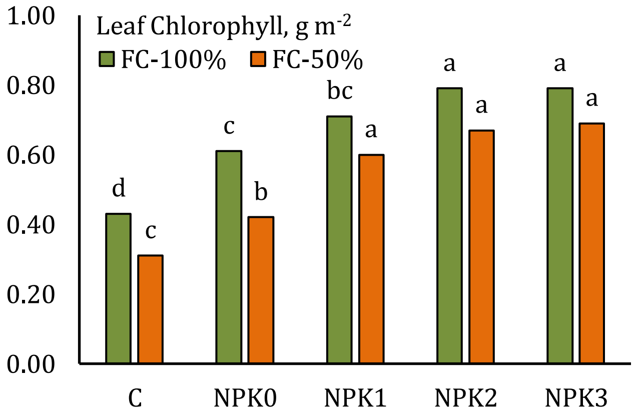


Figure 3. Leaf chlorophyll % of maize as affected by K application rate under two field capacity (FC) water contents. Columns with similar letters are not significantly different at P≤0.05.

Treatment effect on P and K uptake is shown in Figure 4 and Figure 5, respectively. Uptake of P and K was the lowest for the control treatments under both soil moisture contents. In addition, P and K uptake was lower for all treatment under deficit moisture content. Compared to the control treatment, the addition of NPK0 increased P and K uptake, then increased further with the highest two K rates. The increase in P uptake with K application was unpredictable but might be attributed to the indirect effect on shoot dry weight. As for K uptake, the increase was directly due to increasing the rate of K application up to the NPK2. This coincides with the finding of other researchers (Oltmans and Mallarino, 2015; Firmano et al., 2020; Volf et al., 2022) and they attributed such increase to the plant luxury consumption of K. On the other hand, the highest K rate (NPK3) reduced K uptake compared to NPK1 and NPK2, which can be attributed to the possible K leaching associated with high K rates under coarse textured soil as the case in our study (Rosolem and Stainer, 2017).

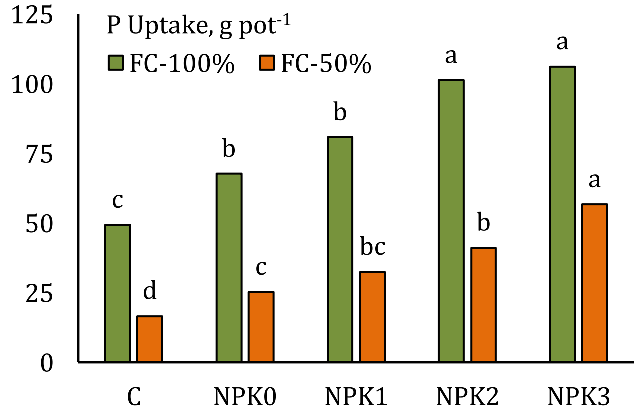


Figure 4. P uptake by maize as affected by K application rate under two field capacity (FC) water contents. Columns with similar letters are not significantly different at P≤0.05.

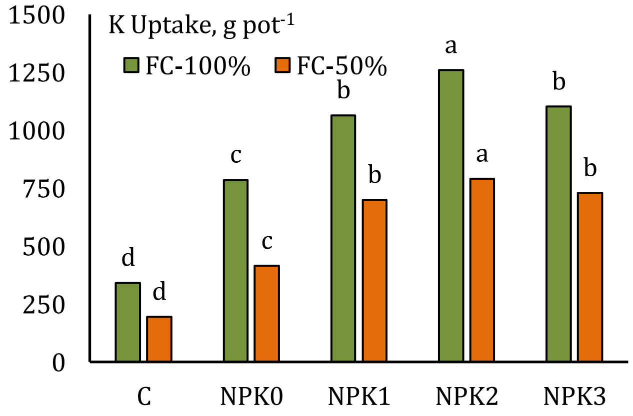


Figure 5. K uptake by maize affected by K application rate under two field capacity (FC) water contents. Columns with similar letters are not significantly different at P≤0.05.

Treatments effect on soil pH and soil EC are shown in Figure 6 and Figure 7, respectively. Soil pH was not affected by any of the treatments. Soil EC was the lowest for the control and then for the NPK0 treatment. Increasing K application rates significantly increased soil EC, due to the relatively high salt index of the applied potassium sulfate (Rusan, 2023).

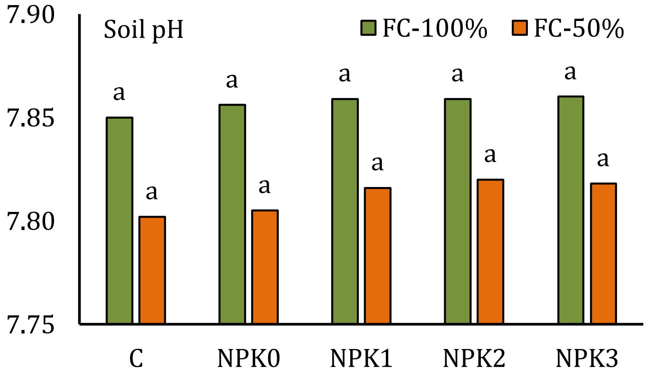


Figure 6. Soil pH as affected by K application rate under two field capacity (FC) water contents. Columns with similar letters are not significantly different at P≤0.05.

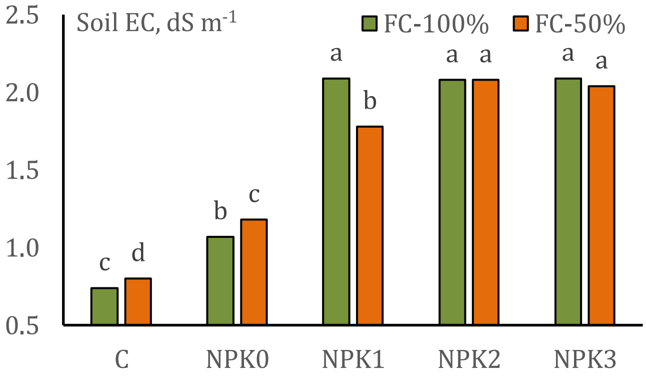


Figure 7. Soil EC as affected by K application rate under two field capacity (FC) water contents. Columns with similar letters are not significantly different at P≤0.05.

Treatments effect on soil N, P and K contents at the end of the experiment are presented in Figure 8, Figure 9 and Figure 10, respectively. Soil N was not significantly affected by the treatments under both soil moisture contents. On the other hand, and compared to the control treatment, soil P increased similarly by all other treatments under adequate soil moisture contents. However, under deficit moisture, the highest rate of K reduced P uptake, which can be due to competition between high rate of K and P (Studer et al., 2017) or might be due the indirect effect of K on P uptake through increasing dry weight. On the other hand, soil K was the lowest for the control and the NPK0 treatments. Increasing the rates of applied K, resulted in higher soil K under both adequate and deficit irrigation conditions.

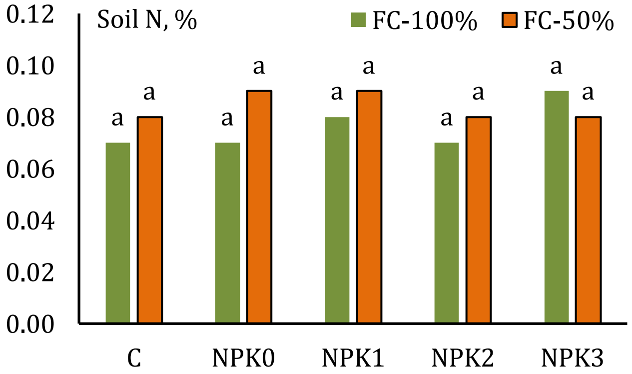


Figure 8. Soil N content as affected by K application rate under two field capacity (FC) water contents. Columns with similar letters are not significantly different at P≤0.05.

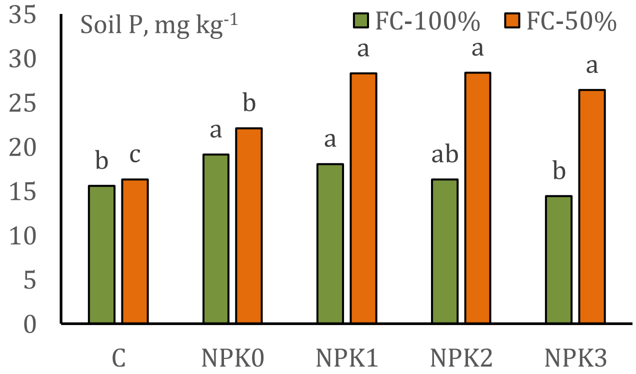


Figure 9. Soil P content as affected by K application rate under two field capacity (FC) water contents. Columns with similar letters are not significantly different at P≤0.05.

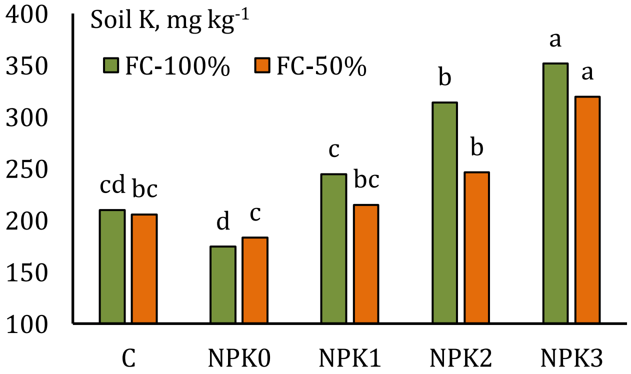


Figure 10. Soil K content as affected by K application rate under two field capacity (FC) water contents. Columns with similar letters are not significantly different at P≤0.05.

Conclusion

Based on the obtained results, it can be concluded that maize growth in sandy loam soil is severely reduced under deficit irrigation level, especially when grown under poor level of soil nutrients. Potassium was necessary to be applied in combination with NP to achieve the possible highest plant growth. The NPK2 dose application (305 kg K_2O/ha) not only gave the highest plant growth and nutrient uptake but also enhanced plant tolerance to water stress conditions. This also suggests including K fertilization as one of the strategies to combat drought stress in arid and semi-arid environment.

Acknowledgement

This study was funded by the Deanship for scientific research at Jordan University of Science and Technology.

References

Ali, A., Hussain, M., Habib, H.S., Kiani, T.T., Anees, M.A., Rahman, M.A., 2016. Foliar spray surpasses soil application of potassium for maize production under rainfed conditions. *Turkish Journal of Field Crops* 21: 36-32.

Amanullah, Iqbal, A., Irfanullah, Hidayat, Z., 2016. Potassium management for improving growth and grain yield of maize (Zea mays L.) under moisture stress condition. *Scientific Reports* 6: 34627.

Asgharipour, M.R., Heidari, M., 2011. Effect of potassium supply on drought resistance in sorghum: Plant growth and macronutrient content. *Pakistan Journal of Agricultural Sciences* 48(3): 197-204.

Aslam, M., Maqbool, M.A., Cengiz, R., 2015. Drought stress in maze (Zea mays L.): Effects, resistance, global achievements and biological strategies for ımprovement. Springer Cham. 74p.

Athamenh, B.M., Salem, N.M., El-Zuraiqi, S.M., Suleiman, W., Rusan, M.J., 2015. Combined land application of treated wastewater and biosolids enhances crop production and soil fertility. *Desalination and Water Treatment* 53(12): 3289-3294.

Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen-Total. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Page, A.L., Miller, R.H., Keeney, D.R., (Eds.). American Society of Agronomy, Soil Science Society of America, Madison, Wisconsin, USA. pp. 595-624.

Brownlie, W.J., Alexander, P., Maslin, M., Canedo, A.M., Sutton, M.A., 2024. Global food security threatened by potassium neglect. *Nature Food* 5: 111–115.

Cakmak, I., 2010. Potassium for better crop production and quality. *Plant and Soil* 335: 1-2.

Caliskan, B., Caliskan, A.C., 2018. Potassium nutrition in plants and its interactions with other nutrients in hydroponic culture. In: Potassium - improvement of quality in fruits and vegetables through hydroponic nutrient management. Asaduzzaman, M., Asao, T. (Eds.). InTech

Chapman, H.D., Pratt, F.P., 1961. Methods of analysis for soils, plants and water. University of California, Division of Agricultural Sciences, Berkeley, USA. 309p.

Das, D., Dwivedi, B.S., Datta S.P., Datta, S.C., Meena, M.C., Datta, S.C., 2020. Intensive cropping with varying nutrient management options alters potassium dynamics in soil. *Indian Journal of Fertilizers* 16(7): 690–704.

Das, D., Dwivedi, B.S., Datta, S.P., Datta, S.C., Meena, M.C., Dwivedi, A.K.., Singh, M., Singh, V.K., Chakraborty, D., Jaggi, S., 2019. Long-term fertilization effects on soil potassium and crop yields in a Vertisol. *Indian Journal of Agricultural Sciences* 89: 1086–1890.

Das, D., Sahoo, J., Raza, M.B., Barman, M., Das, R., 2022. Ongoing soil potassium depletion under intensive cropping in India and probable mitigation strategies. A review. *Agronomy for Sustainable Development* 42: 4.

Efeoğlu, B., Ekmekçi, Y., Çiçek, N., 2009. Physiological responses of three maize cultivars to drought stress and recovery. *South African Journal of Botany* 75(1): 34-42.

FAO, 1999. Global information and early warning system on food and agriculture world food program, FAO/WFP Crop and food supply assessment mission to the kingdom of Jordan. Food and Agriculture Organization of United Nations (FAO)/ World Food Programme (WFP), Rome, Italy.

Firmano, R.F., de Oliveira, A., de Castro, C., Alleoni, L.R.F., 2020. Potassium, rate on the cationic balance of an oxisol and soybean nutritional status after 8 years of K deprivation. *Experimental Agriculture* 56: 294-311.

Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Methods of soil analysis. Part 2 Physical and mineralogical methods. Klute, A. (Ed.). American Society of Agronomy, Soil Science Society of America, Madison, Wisconsin, USA. pp. American Society of Agronomy, Soil Science Society of America, Madison, Wisconsin, USA. pp. 383-411.

Gitelson, A.A., Buschmann, C., Lichtenthaler, H.K., 1999. The Chlorophyll Fluorescence Ratio F_{735}/F_{700} as an accurate measure of the chlorophyll content in plants. *Remote Sensing of Environment* 69: 296–302.

Gopalakrishna, K. N., Hugar, R., Rajashekar, M.K., Jayant, S.B., Talekar, S.C., Virupaxi, P. C., 2023. Simulated drought stress unravels differential response and different mechanisms of drought tolerance in newly developed tropical field corn inbreds. *PLoS ONE* 18(3): e0283528.

Hammad, S.A.R., Ali, O.A.M., 2014. Physiological and biochemical studies on drought tolerance of wheat plants by application of amino acids and yeast extract. *Annals of Agricultural Sciences* 59(1): 133-145.

Hammer, G.L., Dong, Z., McLean, G., Doherty, A., Messina, C., Schussler, J., Zinselmeier, C., Paszkiewicz, S., Cooper, M.. 2009. Can changes in canopy and/or root system architecture explain historical maize yield trends in the U.S. Corn Belt? *Crop Science* 49(1): 299–312.

Hasanuzzaman, M., Bhuyan, M., Nahar, K., Hossain, M., Mahmud, J., Hossen, M., Masud, A., Fujita, M., 2018. Potassium: A vital regulator of plant responses and tolerance to abiotic stresses. *Agronomy* 8(3): 31.

Hassan, M.U., Aamer, M., Chattha, M.U., Ullah, M.A., Sulaman, S., Nawaz, M., Zhiqiang, W., Yanqin, M., Guoqin, H., 2017. The role of potassium in plants under drought stress: Mini review. *Journal of Basic and Applied Sciences* 13: 268-271.

Kang, H., Sridhar, V., Ali, S.A., 2022. Climate change impacts on conventional and flash droughts in the Mekong River Basin. *Science of The Total Environment* 838(2):155845.

Karimpour, M., 2019. Effect of drought stress on RWC and chlorophyll content on wheat (Triticum durum L.) genotypes. *World Essays Journal* 7: 52-56.

Khalid, K.A., Shedeed, M.R., 2015. Effect of NPK and foliar nutrition on growth, yield and chemical constituents in Nigella sativa L. *Journal of Materials and Environmental Science* 6(6): 1709-1714.

Liu, Y., Zhu, Y., Zhang, L., Ren, L., Yuan, F., Yang, X., Jiang S. 2020. Flash droughts characterization over China: From a perspective of the rapid intensification rate. *Science of The Total Environment* 704: 135373.

Lu, D., Li, C., Sokolwski, E., Magen, H., Chen, X., Wang, H., Zhou, J., 2017. Crop yield and soil available potassium changes as affected by potassium rate in rice–wheat systems. *Field Crops Research* 214: 38–44.

Majumdar, K, Norton, R.M., Murrell, T.S., García, F., Zingore, S., Prochnow, L.I., Pampolino, M., Boulal, H., Dutta, S., Francisco, E., Tan, M.S., He, P., Singh, V.K., Oebrthür, T., 2021 Assessing potassium mass balances in different countries and scales. In: Improving potassium recommendations for agricultural crops. Murrell, T.S., Mikkelsen, R.L., Sulewski, G., Norton, R., Thompson, M.L. (Eds.). Springer, Cham, pp. 283–340.

McLean, A.O., 1982. Soil pH and lime requirement. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Page, A.L., Miller, R.H., Keeney, D.R., (Eds.). American Society of Agronomy, Soil Science Society of America, Madison, Wisconsin, USA. pp. 199-224.

Nelson, D.W., Sommers, L.E., 1980. Total nitrogen analysis for soil and plant tissues. *Journal of Association of Official Analytical Chemists* 63(4): 770–778.

Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. U.S. Department of Agriculture, Circular No 939, USA, 19p.

Oltmans, R.R., Mallarino,A.P., 2015. Potassium uptake by corn and soybean, recycling to soil, and impact on soil test potassium. *Soil Science Society of America Journal* 79(1): 314-327.

Palemio, M., Rhoades, J.D., 1977. Determining cation exchange capacity: a new procedure for calcareous and gypsiferous soils. *Soil Science Society of America Journal* 41(3): 524–528.

Pettigrew, W.T., 2008. Potassium influences on yield and quality production for maize, wheat, soybean and cotton. *Physiologia Plantarum* 133(4): 670-681.

Qing, Y., Wang, S., Ancell, B., Yang, Z., 2022. Accelerating flash droughts induced by the joint influence of soil moisture depletion and atmospheric aridity. *Nature Communications* 13: 1139.

Regmi, A.P., Ladha, J.K., Pasuquin, E., Pathak, H., Hobbs, P.R., Shrestha, L.L., Gharti, D.B., Duveiller, E., 2002. The role of potassium in sustaining yields in a long-term rice-wheat experiment in the Indo-Gangetic plains of Nepal. *Biology and Fertility of Soils* 36: 240-247.

Rengel, Z., Damon, P.M., 2008. Crops and genotypes differ in efficiency of potassium uptake and use. *Physiologia Plantarum* 133(4): 624-636.

Rhoades, J.D., 1982. Soluble salts. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Page, A.L., Miller, R.H., Keeney, D.R., (Eds.). American Society of Agronomy, Soil Science Society of America, Madison, Wisconsin, USA. pp. 167–179.

Rosolem, C.A., Steiner, F., 2017. Effects of soil texture and rates of K input on potassium balance in tropical soil. *European Journal of Soil Science* 68(5): 658-666.

Römheld, V., Kirkby, E.A., 2010. Research on potassium in agriculture needs and prospects. *Plant and Soil* 335:155-180.

Rusan, M.J., 2023. Soil and nutrient management under saline conditions. In: Biosaline agriculture as a climate change adaptation for food security. Choukr-Allah, R., Ragab, R. (Eds.). Springer, Cham. pp. 71-85.

Rutkowska, A., Pikuła, D., Stępień, W., 2014. Nitrogen use efficiency of maize and spring barley under potassium fertilization in long-term field experiment. *Plant, Soil and Environment* 60: 550-554.

Siddiqui, M.H., Al-Whaibi, M.H., Sakran, A.M., Basalah, M.O., Ali, H.M., 2012. Effect of calcium and potassium on antioxidant system of Vicia faba L. under cadmium stress. *International Journal of Molecular Sciences* 13(6): 6604-6619.

Song, Y., Birch, C., Qu, S., Doherty, A., Hanan, J., 2010. Analysis and modelling of the effects of water stress on maize growth and yield in dryland conditions. *Plant Production Science* 13: 199- 208.

Studer, C., Hu, Y., Schmidhalter, U., 2017. Interactive effects of N-, P- and K-nutrition and drought stress on the development of maize seedlings. *Agriculture* 7(11):90.

Talal, D., Fadel, A., Safaa, B., Ihan, J., Mohamad, A., Zeina, H., Ousama, H., Therese, A., 2015. Potato performance under different potassium levels and deficit irrigation in dry sub-humid Mediterranean conditions, International Potash

Institute, e-ifc No. 43. Available at [Access date: 30.03.2024]: https://www.ipipotash.org/uploads/udocs/e-ifc-43-potato-lebanon.pdf

Thomas, G.W., 1982. Exchangeable cations. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Page, A.L., Miller, R.H., Keeney, D.R., (Eds.). American Society of Agronomy, Soil Science Society of America, Madison, Wisconsin, USA. pp. 159–165.

Vennam, R.R.. Ramamoorthy, P., Poudel, S., Reddy, K.R., Henry, W.B., Bheemanahalli, R., 2023. Developing functional relationships between soil moisture content and corn early-season physiology, growth, and development. *Plants* 12(13): 2471.

Volf, M.R., Natista-Silva, W., Silvério, A.D., Santos, L.G., Tiritan, C.S., 2022. Effect of potassium fertilization in sandy soil on the content of essential nutrients in soybean leaves. *Annals of Agricultural Sciences* 67: 99-106.

Wach, D., Skowron, P., 2022. An overview of plant responses to the drought stress at morphological, physiological and biochemical levels. *Polish Journal of Agronomy* 50: 25–34.

Wang, M., Zheng, Q., Shen, Q., Guo, S., 2013. The critical role of potassium in plant stress response. *International Journal of Molecular Sciences* 14(4):7370-7390.

Xiang, D.B., Peng, L.X., Zhao, J.L., Zou, L., Zhao. G., Song. C., 2013. Effect of drought stress on yield, chlorophyll contents and photosynthesis in tartary buckwheat (Fagopyrum tataricum). *Journal of Food Agriculture and Environment* 11(3): 1358-1363.

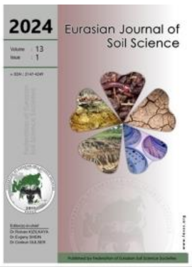
Yousaf, M.I., Riaz, M.W., Shehzad, A., Jamil, S., Shahzad, R., Kanwal. S., Ghani. A/, Ali, F., Abdullah, M., Ashfaq, M., Hussain, Q., 2023. Responses of maize hybrids to water stress conditions at different developmental stages: accumulation of reactive oxygen species, activity of enzymatic antioxidants and degradation in kernel quality traits. *PeerJ* 11: e14983.

Zorb, C., Senbayram, M., Peiter, E., 2014. Potassium in agriculture – Status and perspectives. *Journal of Plant Physiology* 171(9): 656-669.

Eurasian Journal of Soil Science 2024, 13(4), 328 - 337

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



Impact of phosphorus fertilization on the yield and quality of various Alfalfa (*Medicago sativa* L.) varieties in light chestnut soils

Nariman Massaliyev [a], Sara Ramazanova [b], Karlyga Karayeva [a,*], Zhuldyz Oshakbayeva [c], Aigul Zhamangarayeva [a], Ashirali Smanov [a], Nurymzhan Aubakirov [a], Saken Duisekov [d]

[a] Kazakh National Agrarian Research University, Almaty, Kazakhstan
[b] Kazakh Research Institute of Agriculture and Plant Growing, Almaty District, Almalybak, Kazakhstan
[c] Kostanay Engineering and Economics University named after M.Dulatov, Kostanay, Kazakhstan
[d] Kazakh Research Institute of Soil Science and Agrochemistry named after U.U.Uspanov, Almaty, Kazakhstan

Article Info
Received : 01.12.2023
Accepted : 19.07.2024
Available online: 23.07.2024

Author(s)
N.Massaliyev
S.Ramazanova
K.Karayeva *
Z.Oshakbayeva
A.Zhamangarayeva
A.Smanov
N.Aubakirov
S.Duisekov

* Corresponding author

Abstract

This study investigates the impact of phosphorus fertilization on the yield and quality of various alfalfa (*Medicago sativa* L.) varieties grown in light chestnut soils. Conducted over a three-year period from 2013 to 2015, the research was carried out in the Karasay district of the Almaty region under irrigated conditions. The experiment included six alfalfa varieties: NS Alfa, VS Banat, Mediana, Nera, Niagara, and Kokoray. Four phosphorus treatments were applied: control (no phosphorus), 60 kg/ha (P60), 90 kg/ha (P90), and 120 kg/ha (P120), using double superphosphate as the phosphorus source. The results demonstrated that phosphorus fertilization significantly enhanced both the yield and quality of alfalfa. Across all varieties, the highest yield was observed with the application of 120 kg/ha phosphorus. For instance, NS Alfa's yield increased from 283.3 c/ha in the control to 349.7 c/ha with P120, reflecting a 23% increase. Similarly, VS Banat and Mediana exhibited yield increases of 23% and 25%, respectively, at the highest phosphorus level. The study also revealed improvements in the nutritional quality of alfalfa hay. Crude protein content increased from 20.3% to 22.0% in NS Alfa, while digestible protein content rose from 11.20% to 12.40%. Other quality parameters, including fat and carotene content, also improved significantly with higher phosphorus levels. Moreover, the availability of nitrate nitrogen and mobile phosphorus in the soil increased progressively with higher phosphorus application rates, contributing to better nutrient uptake and overall plant health. This research underscores the importance of phosphorus fertilization in maximizing alfalfa yield and quality. The findings suggest that the optimal phosphorus application rate for enhancing alfalfa production in light chestnut soils is 120 kg/ha, providing valuable insights for sustainable agricultural practices in similar agro-ecological zones.

Keywords: Phosphorus fertilization, Alfalfa yield, Alfalfa quality, Light chestnut soils, Sustainable agriculture.

Introduction

Phosphorus is one of the essential macronutrients required for plant growth and development. It is a key component of ATP, nucleic acids, and phospholipids, all of which are vital for energy transfer, genetic information storage, and membrane integrity in plants (Marschner, 1995; Khan et al., 2023). Phosphorus deficiency can severely limit plant growth, leading to reduced biomass production and poor crop quality. This

---

: https://doi.org/10.18393/ejss.1521142
: https://ejss.fesss.org/10.18393/ejss.1521142
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

is particularly significant in leguminous crops like alfalfa, which have high phosphorus requirements to support their vigorous growth and nitrogen-fixing capabilities (Meng et al., 2021).

Alfalfa (*Medicago sativa* L.), known as the 'Queen of Forages', is one of the oldest wild plants, originally found in the mountainous forests of the Mediterranean region in Southwest Asia. The name 'alfalfa' is derived from the Arabic word 'Al-Fasfasa', which means 'father of all plants' (Suwignyo et al., 2022). Alfalfa is a highly valued forage crop known for its high nutritional content and adaptability to various environmental conditions. It is widely cultivated for its high protein content and digestibility, making it an essential component of livestock diets. The demand for high-quality alfalfa hay has increased, emphasizing the need for improved cultivation practices to enhance both yield and nutritional value (Capstaff and Miller, 2018). The importance of alfalfa in sustainable agriculture cannot be overstated, as it plays a crucial role in improving soil structure, enhancing soil fertility, and providing high-quality forage for animals (Xu et al., 2024). Previous studies (Berg et al., 2005; Macolino et al., 2013; Liu et al., 2013; Madani et al., 2014; Al-Kahtani et al., 2017; Li and Liu, 2024) have shown that phosphorus fertilization can significantly improve the growth and productivity of alfalfa by enhancing root development and increasing the availability of essential nutrients in the soil. Studies have shown that phosphorus application enhances root development, increases nutrient uptake, and improves overall plant health, leading to higher yields and better quality forage. For instance, Yıldız and Türk (2015) reported that phosphorus fertilization significantly increased biomass production in forage crops, while Marschner (1995) and Havlin et al. (2005) emphasized the importance of phosphorus in improving soil fertility and crop productivity.

Light chestnut soils, which are prevalent in many agricultural regions, often exhibit low phosphorus availability due to their high calcium carbonate content and alkaline pH (Saparov, 2014). This characteristic makes these soils less suitable for high-yielding crops without appropriate fertilization strategies (Maxotova et al., 2021; Zhaksybayeva et al., 2022; İslamzade et al., 2023). To address this challenge, it is crucial to determine the optimal phosphorus application rates that can maximize alfalfa yield and quality while maintaining soil health.

Despite the well-documented benefits of phosphorus fertilization, there is limited research specifically addressing its impact on the yield and quality of different alfalfa varieties grown in light chestnut soils. This study aims to fill this gap by evaluating the effects of various phosphorus application rates on the growth, yield, and nutritional quality of several alfalfa varieties under irrigated conditions in the Almaty region. The findings will provide valuable insights for optimizing fertilization strategies to maximize alfalfa productivity and quality in similar agro-ecological zones. The objective of this study is to assess the impact of different levels of phosphorus fertilization on the yield and quality of various alfalfa varieties grown in light chestnut soils, thereby identifying the optimal phosphorus application rate for enhancing alfalfa production in these conditions.

Material and Methods

Experimental site

The research was conducted from 2013 to 2015 in irrigated light chestnut soils at the Kazakh Research Institute of Agriculture and Plant Growing located in the Karasay district of the Almaty region, Kazakhstan (Figure 1).

Figure 1. Experimental area

The soil of the experimental area belongs to the general soil type of light chestnut. Before conducting the experiment, the soil sample was analyzed by the Kazakh National Agrarian Research University. Some characteristics of the experimental field's soil are presented in Table 1.

Table 1. Some characteristics of the experimental field's soil

Depth (cm)	Organic matter (%)	Total Nitrogen (%)	Mobile Nitrogen (mg/kg)	Mobile Phosphorus (mg/kg)	Mobile Potassium (mg/kg)	Bulk Density (g/cm^3)
0-20	2.45	0.193	73.8	25.0	460	1.20
20-40	2.30	0.156	71.9	20.1	430	1.25

Climatic data

The experimental area has a continental climate with hot summers and cold winters, and low precipitation. Despite occasional high rainfall, irrigation is essential for high forage crop yields. The region experiences an average of 219 days per year with temperatures above +5ºC. In the Almaty region, the transition from negative to positive average daily temperatures occurs between March 5 and 10. January, the coldest month, has average temperatures between -1.9ºC and -7.6ºC, while July, the hottest month, ranges from +27.8ºC to +31.4ºC. The frost-free period lasts 5-6 months. Annual precipitation averages 332-645 mm, with the most rainfall from March to June. In arid years, rainfall can be 1.5-2.0 times below average, while in wet years, it can exceed the norm by the same ratio. Snow cover lasts 1.5 to 3.0 months, with depths not exceeding 15-20 cm. The monthly temperature and precipitation averages for the Karasay District, where the experimental field is located, are presented in Figure 2.

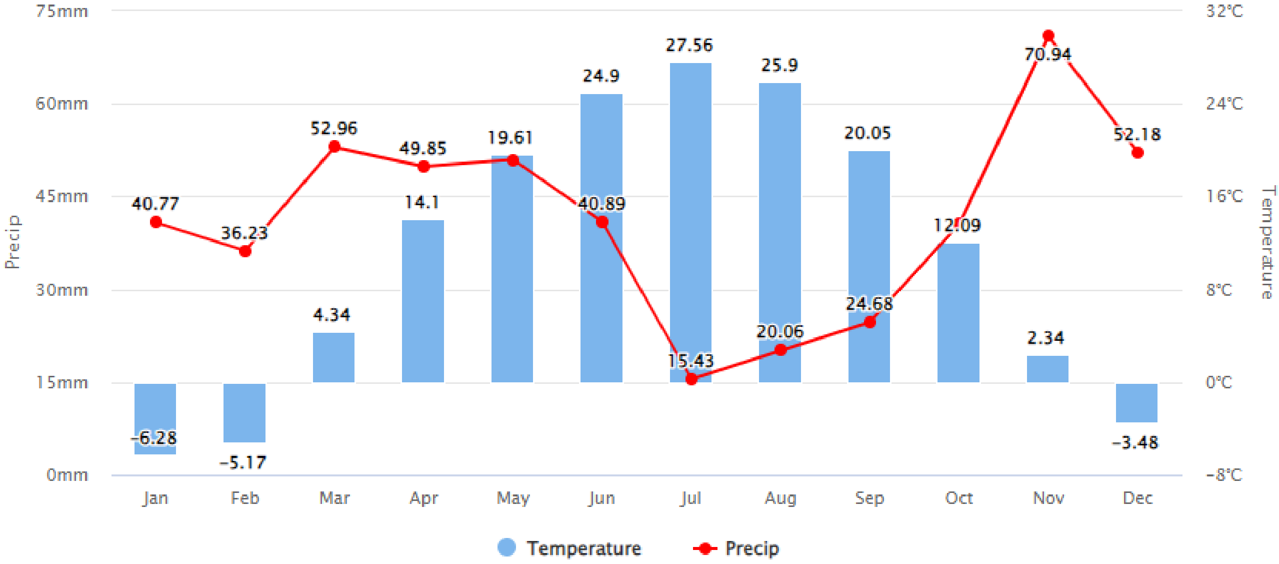


Figure 2. Temperature and precipitation averages in the Karasay District (in Almaty Region, Kazakhstan) where the experimental field is located

Alfalfa (Medicago sativa L.) varieties

Six alfalfa varieties were used in the experiment, including the local Kazakh variety, Kokoray, and five Serbian varieties: NS Alfa, VS Banat, Mediana, Nera, and Niagara. VS Banat is an early variety with rapid growth and good drought and cold tolerance, yielding 85-100 t/ha of green mass and 18-20 t/ha of hay, with 20.1% protein content. NS Alfa, a synthetic variety, thrives in fertile soils, is cold-resistant, and supports frequent mowing, producing over 80 t/ha of green mass and 20 t/ha of hay, with 20-22% protein content. Niagara is disease-resistant, drought-tolerant, and performs well on degraded soils, yielding over 80 t/ha of green mass and 20 t/ha of hay, with 22% protein content. Nera, an early variety with a deep root system, is drought-resistant and regenerates quickly, yielding over 80 t/ha of green mass and 20 t/ha of hay, with 20.7% protein content. NS Mediana, developed through hybridization, grows well in various conditions, is drought and cold-resistant, and yields about 20 t/ha of hay, with an average protein content of 21%.

Experimental Design

The alfalfa was sown using specialized equipment with a row spacing of 15 cm, and a seeding rate of 16 kg per hectare. The experimental design was a randomized complete block design, with each treatment repeated three times. Each plot measured 15 meters in length and 1 meter in width, resulting in a total plot area of 15 m^2 for each alfalfa variety. Double superphosphate (42% P_2O_5) was used as the phosphorus source for all treatments.

The experiment included four phosphorus fertilizer treatments:

- Control: No phosphorus fertilizer applied.
- P60: 60 kg/ha of phosphorus applied.
- P90: 90 kg/ha of phosphorus applied.
- P120: 120 kg/ha of phosphorus applied.

Soil and Plant Analysis Methods

During the trial period, nitrate nitrogen in soil samples taken from each plot at the stages of the 1st cutting, 2nd cutting, 3rd cutting, and 4th cutting of alfalfa varieties was determined using the Kjeldahl distillation method in 1N KCl extract, and mobile phosphorus was determined according to the Machigin method (Jones, 2001). At the end of the trial, yield and yield components (Crude Protein, N-free Extractives, Cellulose, Ca, Ash, Carotene, Fat, Digestible protein) in alfalfa variety samples taken from all plots were determined as reported by Galyean (2010).

Results and Discussion

Yield of Alfalfa

The application of phosphorus fertilizers significantly increased the yield of alfalfa across all varieties studied from 2013 to 2015. The different levels of phosphorus application (60, 90, and 120 kg/ha) showed a marked improvement in yield compared to the control (Table 2).

Table 2. Yield of Alfalfa varieties depending on the use of phosphorus fertilizer (2013-2015)

Variety	Treatment	2013 Yield (t/ha)	2014 Yield (t/ha)	2015 Yield (t/ha)	Total Yield (c/ha)	Additional Yield (c/ha)	Increase (%)
NS Alfa	Control	27.1	129.2	127.0	283.3	-	-
	P60	30.1	145.4	138.8	314.3	31.0	11
	P90	30.7	148.5	141.4	320.6	37.3	13
	P120	43.0	155.9	150.8	349.7	66.4	23
VS Banat	Control	28.0	130.9	124.5	283.4	-	-
	P60	28.8	147.9	143.9	320.6	37.2	13
	P90	29.8	151.2	148.0	329.0	45.6	16
	P120	32.4	161.0	155.4	348.8	65.4	23
Mediana	Control	25.1	126.4	122.9	274.4	-	-
	P60	33.2	134.3	134.3	301.8	27.4	10
	P90	30.7	144.7	137.8	313.2	38.8	14
	P120	37.0	153.2	153.2	343.4	69.0	25
Nera	Control	23.2	115.5	107.1	245.8	-	-
	P60	29.0	127.1	120.3	276.4	30.6	12
	P90	28.0	135.2	126.2	289.6	43.8	18
	P120	33.2	148.6	148.6	330.4	84.6	34
Niagara	Control	19.8	122.6	111.7	254.1	-	-
	P60	26.1	132.4	122.2	280.7	26.6	10
	P90	28.4	139.1	131.1	298.6	44.5	18
	P120	41.0	145.3	141.1	327.4	73.3	29
Kokoray	Control	27.1	123.5	113.4	264.0	-	-
	P60	30.1	144.9	145.0	320.0	56.0	21
	P90	30.7	151.0	142.2	323.9	59.9	22
	P120	35.0	155.9	150.0	340.9	76.9	29

In 2013, the initial yields were relatively lower across all varieties and treatments, possibly due to the initial establishment periods of the alfalfa. However, as phosphorus application rates increased, yields showed noticeable improvement. For example, NS Alfa exhibited a marked increase from 27.1 t/ha in the control to 43.0 t/ha with 120 kg/ha phosphorus in 2013. This trend continued in subsequent years, with the highest increases observed in 2015, where NS Alfa achieved a yield of 349.7 c/ha, representing a 23% increase over the control.

VS Banat and Mediana also showed considerable yield improvements. VS Banat's yield increased from 28.0 t/ha in the control to 32.4 t/ha with 120 kg/ha phosphorus in 2013. By 2015, this variety achieved a total yield of 348.8 c/ha, reflecting a 23% increase. Mediana's yield improved from 25.1 t/ha in the control to 37.0 t/ha with 120 kg/ha phosphorus in 2013, with a total yield of 343.4 c/ha by 2015, representing a 25% increase.

Kokoray exhibited the highest yield increase of 21% with 60 kg/ha phosphorus in 2013. By 2015, with 120 kg/ha phosphorus, Kokoray's yield reached 340.9 c/ha, representing a 29% increase. This substantial increase underscores the effectiveness of phosphorus in enhancing the productivity of this variety.

The application of 90 kg/ha phosphorus resulted in significant yield increases for all varieties. NS Alfa's yield increased by 13%, VS Banat by 16%, and Mediana by 14%. These results are consistent with findings from similar studies that highlight the critical role of phosphorus in improving crop yield by enhancing nutrient uptake and utilization efficiency (Havlin et al., 2005; Yıldız and Türk, 2015). The highest efficiency was observed with the application of 120 kg/ha phosphorus. This level of application resulted in the most significant yield increases across all varieties, with NS Alfa, VS Banat, and Mediana achieving yields of 349.7 c/ha, 348.8 c/ha, and 343.4 c/ha, respectively. Nera and Niagara also showed notable yield increases, with Nera's yield increasing by 34% and Niagara by 29%. These results highlight the optimal rate of phosphorus application necessary to maximize alfalfa yield, corroborating studies that advocate for balanced fertilization strategies to achieve sustainable high yields (Berg et al.; 2005; Madani et al., 2014; Al-Kahtani et al., 2017; Maxotova et al., 2021; Alimkhanov et al., 2021; Kamzina et al., 2022; Muminova et al., 2022).

These findings emphasize the importance of phosphorus fertilization in maximizing the yield of alfalfa varieties. The application of 120 kg/ha phosphorus was identified as the most effective rate for achieving the highest yield improvements across all studied varieties. This rate not only enhanced yield but also improved the overall quality of the alfalfa, making it a critical component of alfalfa cultivation practices in light chestnut soils. Phosphorus fertilizer is a key factor affecting seed yield and has a significant impact on the dynamic changes in plant stems, inflorescence number, dry matter accumulation, and seed yield (Liu et al., 2020; Loeppky et al., 1999). Liu et al. (2013) reported that under alkaline soil conditions in arid areas, a phosphorus fertilizer dosage of 150 kg/ha can promote an increase in alfalfa seed yield when the soil phosphorus content reaches a moderate level. Buglass (1964) indicated that there was no significant role for phosphorus in increasing forage seed production in southern Saskatchewan, reflecting the variability of soil phosphorus status and the influence of annual weather effects. In this experiment, when phosphorus fertilizer was applied at 120 kg/ha, the yield increased by 25% and 34% compared to the control, respectively, in each year. This indicates that phosphorus fertilizer can increase the seed yield of alfalfa, but the effect is related to the selected alfalfa varieties, climatic conditions, soil conditions, and phosphorus fertilizer application (Al-Kahtani et al., 2017; Liu et al., 2013).

Quality of Alfalfa

The quality of alfalfa, as measured by its nutritional content, improved significantly with the application of phosphorus fertilizers. The study examined various parameters such as crude protein (CP), digestible protein (DP), non-nitrogenous extractives (NNE), fat content, and carotene content across different varieties of alfalfa (Table 3).

The application of phosphorus fertilizer had a notable impact on the crude and digestible protein content in all alfalfa varieties. NS Alfa showed an increase in crude protein from 20.3% in the control to 22.0% with 120 kg/ha phosphorus, and digestible protein increased from 11.20% to 12.40%. Similarly, VS Banat's crude protein content increased from 21.8% to 24.0%, and digestible protein from 10.0% to 11.35%. Mediana's crude protein rose from 22.3% to 24.5%, and digestible protein from 11.80% to 14.0%. An increase in crude and digestible protein content led to a decrease in non-nitrogenous extractives content. For instance, phosphorus fertilizer reduced non-nitrogenous extractives from 35.8% to 24.7% in NS Alfa, and similar reductions were observed in other varieties. This aligns with the findings of Sumner and Farina (1986) and Xu et al. (2024), who noted that phosphorus application can enhance protein content while reducing non-nitrogenous extractives in forage crops.

Phosphorus fertilizer also positively affected the fat and carotene content of alfalfa hay. The application of 120 kg/ha phosphorus increased the fat content in NS Alfa to 2.8%, compared to 2.0% in the control. Similar increases were observed in other varieties, such as VS Banat and Niagara, where fat content rose to 2.8% and 2.6%, respectively. The carotene content also showed significant improvement with phosphorus application. For example, NS Alfa's carotene content increased from 33.6% in the control to 36.7% with 120 kg/ha phosphorus. This trend was consistent across other varieties, with notable increases in VS Banat, Mediana, and Nera. There are genetic variations in yield and its components among and within populations of alfalfa (Campbell and He, 1997) and the response of yield components to plant genetics and management techniques is also different (El-Hifny et al.,2019; Sengul, 2006). Yield and its components exhibit genetic variability both among and within alfalfa populations (Campbell and He, 1997). Additionally, the response of these yield components to plant genetics and various management techniques varies significantly (El-Hifny et al., 2019; Sengul, 2006). This nuanced understanding is crucial for tailoring effective agricultural practices, particularly in projects focused on enhancing crop yield and quality.

Table 3. Effect of Phosphorus Fertilizer on the Composition of Alfalfa Hay

Variety	Treatment	Crude Protein (%)	N-free Extractives (%)	Cellulose (%)	Ca (%)	Ash (%)	Carotene (%)	Fat (%)	Digestible Protein (%)
NS Alfa	Control	20.0	30.2	40.0	2.17	9.6	33.6	2.0	11.08
	P60	20.3	30.0	42.0	2.05	10.8	34.8	2.3	11.20
	P90	21.5	29.8	41.8	1.98	11.5	36.0	2.7	11.38
	P120	22.0	30.0	42.8	1.92	12.8	36.7	2.8	12.40
VS Banat	Control	20.1	35.2	30.1	2.80	13.0	40.0	1.8	9.00
	P60	21.8	34.0	32.0	2.77	13.8	41.2	2.0	10.00
	P90	22.4	34.0	32.6	2.61	14.6	43.0	2.1	11.00
	P120	24.0	33.3	34.0	2.52	16.0	43.9	2.3	11.35
Mediana	Control	21.4	28.0	38.0	2.45	11.5	38.0	2.4	9.50
	P60	22.3	27.7	38.2	2.15	12.8	39.0	2.6	11.80
	P90	23.2	25.0	39.0	1.90	13.3	40.5	2.9	12.44
	P120	24.5	25.1	40.8	1.87	15.8	41.0	2.8	14.00
Nera	Control	20.7	36.8	29.4	2.30	9.6	40.0	1.6	10.00
	P60	21.8	35.7	31.3	2.22	11.2	41.0	1.7	11.20
	P90	22.5	35.8	30.6	2.24	12.4	41.6	1.9	12.60
	P120	23.0	35.1	32.0	2.21	14.4	42.3	1.8	14.80
Niagara	Control	22.0	27.5	33.5	2.18	10.0	38.2	2.2	10.80
	P60	23.0	26.0	35.0	2.14	11.5	39.0	2.3	12.70
	P90	24.5	26.3	37.7	2.06	14.0	40.5	2.5	13.80
	P120	26.0	25.5	39.0	2.00	16.0	41.0	2.6	14.50
Kokoray	Control	15.6	26.0	37.0	2.20	9.9	35.0	1.9	9.06
	P60	17.2	25.0	38.0	2.21	12.0	37.0	2.1	11.00
	P90	17.0	24.8	38.3	2.15	13.2	36.0	2.4	12.51
	P120	17.6	24.7	39.0	2.10	14.6	38.0	2.6	12.90

These results highlight the importance of phosphorus fertilization in enhancing the nutritional quality of alfalfa. The improvements in crude and digestible protein, fat, and carotene contents indicate that phosphorus not only boosts yield but also enriches the nutritional profile of the crop. Such enhancements are crucial for improving the overall feed value of alfalfa, making it more beneficial for livestock. The application of 120 kg/ha phosphorus was particularly effective across all varieties studied, indicating its critical role in improving the nutritional value of alfalfa hay. The findings are supported by previous research, including studies by Wang et al (2008) and Macolino et al. (2015), which emphasize the role of phosphorus in improving forage quality by enhancing nutrient uptake and utilization efficiency.

Nutrient Availability

The nutrient availability in the soil was significantly influenced by the application of phosphorus fertilizers. Throughout the growing season, levels of nitrate nitrogen and mobile phosphorus increased progressively from the initial to the final stages. Initial nitrate nitrogen levels ranged from 50.0 to 60.0 mg/kg during germination, rising significantly by the fourth cutting. For instance, in NS Alfa treated with 60 kg/ha phosphorus, nitrate nitrogen levels increased from 61.5 mg/kg at germination to 70.4 mg/kg after the fourth cutting (Table 4). This pattern was consistent across all varieties, with the highest levels observed in treatments with 120 kg/ha phosphorus (Table 4).

The addition of phosphorus can influence soil nitrogen pools and cycling processes through various impacts on plant growth and microbial activity. For example, phosphorus application can reduce nitrogen leaching losses and retain more nitrogen in plant-soil ecosystems by promoting plant and microbial growth and nitrogen uptake (Baral et al., 2014; Chen et al., 2017). However, it can also increase nitrogen loss through gaseous emissions, such as N_2O, by stimulating nitrification and denitrification processes (Mehnaz et al., 2019; Mori et al., 2013). In phosphorus-limited ecosystems, reductions in N_2O emissions have been observed due to a decline in NO3− availability and reduced denitrification (Chen et al., 2016; Mori et al., 2014; Yu et al., 2017).

Table 4. The effect of phosphorus fertilizers on the amount of nitrate nitrogen (mg/kg) in light chestnut soil of alfalfa crops

Treatment	Variety	Germination	1st Cutting	2nd Cutting	3rd Cutting	4th Cutting	Average
Control	NS Alfa	50.4	52.0	59.2	62.3	66.5	58.0
	VS Banat	55.3	50.0	62.0	65.3	68.0	60.1
	Mediana	50.7	55.8	60.0	62.3	65.0	58.8
	Nera	55.8	60.0	64.0	67.4	70.9	63.5
	Niagara	55.4	58.7	59.2	62.0	68.0	60.5
	Kokoray	53.2	57.0	62.0	65.3	68.0	61.1
P60	NS Alfa	61.5	62.4	65.7	67.0	70.4	65.4
	VS Banat	60.0	66.0	67.7	70.0	75.2	68.7
	Mediana	67.5	69.5	71.5	75.0	78.4	72.2
	Nera	61.0	64.0	66.0	68.8	75.5	67.1
	Niagara	62.0	65.0	68.7	70.0	75.2	68.2
	Kokoray	58.0	61.0	67.0	70.9	78.4	66.9
P90	NS Alfa	68.2	70.0	73.7	71.5	75.0	71.6
	VS Banat	65.5	75.0	76.8	77.5	80.5	75.1
	Mediana	65.2	70.2	75.7	77.4	82.6	74.2
	Nera	65.8	71.5	75.0	78.2	80.2	74.1
	Niagara	68.5	70.0	77.2	74.5	80.5	74.2
	Kokoray	64.5	68.5	76.0	77.0	82.6	73.7

Higher plant and microbial nitrogen uptake following phosphorus addition can also enhance biological nitrogen fixation (Ament et al., 2018; Houlton et al., 2008) and microbial nitrogen mining from soil organic matter (Fisk et al., 2014), thus improving ecosystem nitrogen input and cycling. Conversely, some studies have shown that phosphorus addition has no significant impact on the soil total nitrogen pool and nitrogen availability (McLaren and Buckeridge, 2019; Scott et al., 2015), while others have found a decrease in the total nitrogen pool and nitrogen availability, which was attributed to higher plant uptake and assimilation rates compared to litter-decomposition return rates (Stiles et al., 2017; Yu et al., 2017).

Similarly, mobile phosphorus levels in the soil also showed a marked increase with the application of phosphorus fertilizers. For instance, in the control plots, the mobile phosphorus content ranged from 25.8 to 28.0 mg/kg across the varieties during germination, indicating an average phosphorus supply level. However, in plots treated with 60 kg/ha of phosphorus, the mobile phosphorus levels increased to 23.3-26.5 mg/kg. Further application of 90 kg/ha of phosphorus resulted in mobile phosphorus levels ranging from 27.2 to 31.9 mg/kg (Table 5).

Table 5. The effect of phosphorus fertilizers on the amount of mobile phosphorus (mg/kg) in the light chestnut soil in the alfalfa field

Treatment	Variety	Germination	1st Cutting	2nd Cutting	3rd Cutting	4th Cutting	Average
Control	NS Alfa	26.2	22.5	19.0	18.0	15.5	20.2
	VS Banat	27.4	21.7	19.0	18.5	16.5	20.6
	Mediana	28.0	25.0	23.0	20.0	18.0	22.8
	Nera	27.0	24.0	20.0	20.0	17.0	21.6
	Niagara	25.8	23.4	20.0	17.0	16.5	20.5
	Kokoray	27.0	25.6	22.0	20.5	18.2	22.7
P60	NS Alfa	28.3	25.8	23.5	21.2	20.0	23.8
	VS Banat	29.7	24.8	23.0	20.5	18.5	23.3
	Mediana	30.3	28.2	26.2	24.5	23.0	26.4
	Nera	29.5	25.4	24.0	21.0	20.0	24.0
	Niagara	28.6	27.4	22.5	20.0	18.5	23.4
	Kokoray	29.0	27.5	25.0	19.5	23.0	24.8
P90	NS Alfa	33.1	30.0	26.3	24.0	23.0	27.3
	VS Banat	37.0	28.5	25.7	23.0	22.0	27.2
	Mediana	35.5	33.0	30.0	27.6	26.5	30.5
	Nera	36.7	34.7	31.2	30.4	26.5	31.9
	Niagara	35.5	35.0	24.3	22.5	22.0	27.9
	Kokoray	35.4	32.2	28.7	26.0	26.5	29.8

The results indicated distinct patterns in phosphorus availability influenced by both the applied P fertilizer doses and variety of the alfa alfa plants. Similarly, studies conducted by Medinski et al. (1998), Wu et al. (2020), Wang et al. (2022), Zhaksybayev et al. (2022) and Islamzade et al (2023) have determined that increasing application rates of chemical fertilizers to the soil result in both increased crop yields and improved phosphorus content in the soil.

Conclusion

The study conclusively demonstrated the critical role of phosphorus fertilization in enhancing both the yield and quality of alfalfa crops grown in light chestnut soils. Over the three-year period from 2013 to 2015, it was evident that increasing levels of phosphorus (60, 90, and 120 kg/ha) significantly improved various growth parameters. The yield data highlighted that phosphorus application markedly increased alfalfa productivity across all varieties. The highest efficiency was observed at the 120 kg/ha phosphorus level, where yields saw an increase of up to 34% for certain varieties such as Nera. This finding confirms that phosphorus is vital for root development and energy transfer in plants, leading to enhanced biomass production.

In terms of quality, the application of phosphorus fertilizer positively impacted the nutritional content of alfalfa hay. Increases in crude and digestible protein, fat, and carotene content were observed across all varieties with the highest application rate. This indicates that phosphorus not only boosts yield but also enhances the feed value of alfalfa, making it more beneficial for livestock. Furthermore, the study revealed that phosphorus fertilizer significantly improves the availability of nitrate nitrogen and mobile phosphorus in the soil. This enhanced nutrient availability supports better growth and productivity of alfalfa.

Overall, the application of 120 kg/ha phosphorus was identified as the most effective rate for achieving the highest improvements in yield and quality. The study underscores the multifaceted benefits of phosphorus fertilization in alfalfa cultivation. By optimizing phosphorus application rates, farmers can achieve significant improvements in both yield and quality of alfalfa, while also enhancing soil health. Future research should aim to refine these application rates and investigate the long-term implications of continuous phosphorus use, ensuring sustainable and productive alfalfa farming practices.

References

Alimkhanov, Y., Yeleshev, R., Yertayeva, B., Aitbayeva, A., 2021. Responses of potato (Solanum tuberosum L.) varieties to NPK fertilization on tuber yield in the Southeast of Kazakhstan. *Eurasian Journal of Soil Science* 10(4): 285 - 289.

Al-Kahtani, S.N., Taha, E.A., Al-Abdulsalam, M., 2017. Alfalfa (Medicago sativa L.) seed yield in relation to phosphorus fertilization and honeybee pollination. *Saudi Journal of Biological Sciences* 24(5): 1051-1055.

Ament, M. R., Tierney, J. A., Hedin, L. O., Hobbie, E. A., Wurzburger, N., 2018. Phosphorus and species regulate N_2 fixation by herbaceous legumes in longleaf pine savannas. *Oecologia* 187(1): 281–290.

Baral, B.R., Kuyper, T.W., Van Groenigen, J.W., 2014. Liebig's law of the minimum applied to a greenhouse gas: Alleviation of P-limitation reduces soil N_2O emission. *Plant and Soil* 374(1): 539–548.

Berg, W.K., Cunningham, S.M., Brouder, S.M., Joern, B.C., Johnson, K.D., Santini, J., Volenec, J.J., 2005. Influence of phosphorus and potassium on alfalfa yield and yield components. Crop Science 45: 297–304.

Buglass, E., 1964. Seed production of crested wheatgrass as influenced by various management practices. *Canadian Journal of Plant Science* 44: 66-74.

Campbell, T.A., He, Y., 1997. Factorial analysis of selfincompatibility in alfalfa. *Canadian Journal of Plant Science* 77: 69-73.

Capstaff, N.M., Miller, A.J., 2018. Improving the yield and nutritional quality of forage crops. *Frontiers in Plant Science* 9: 535.

Chen, H., Gurmesa, G. A., Zhang, W., Zhu, X., Zheng, M., Mao, Q., Zhang, T., Mo, J., 2016. Nitrogen saturation in humid tropical forests after 6 years of nitrogen and phosphorus addition: Hypothesis testing. *Functional Ecology* 30(2): 305–313.

Chen, H., Zhang, W., Gurmesa, G. A., Zhu, X., Li, D., Mo, J., 2017. Phosphorus addition affects soil nitrogen dynamics in a nitrogen-saturated and two nitrogen-limited forests. *European Journal of Soil Science* 68(4): 472–479.

El-Hifny, M.Z., Bakheit, B.R., Hassan, M.S., El-Rady, W.A.A., 2019. Forage and seed yield variation of alfalfa cultivars in response to planting date. *SVU-International Journal of Agricultural Science* 1: 21-33.

Fisk, M.C., Ratliff, T.J., Goswami, S., Yanai, R.D., 2014. Synergistic soil response to nitrogen plus phosphorus fertilization in hardwood forests. *Biogeochemistry* 118(1): 195–204.

Galyean, M.L., 2010. Laboratory procedures in animal nutrition research. Texas Tech University, Lubbock. Available at [Access date: 01.12.2023]: https://www.depts.ttu.edu/agriculturalsciences/vetSciences/mgalyean/lab_man.pdf

Havlin, J.L., Beaton, J.D., Tisdale, S.L. Nelson, W.L., 2005. Soil Fertility and Fertilizers: An Introduction to Nutrient Management. 7th Edition, Pearson Educational, Inc., Upper Saddle River, New Jersey. 515p.

Houlton, B.Z., Wang, Y.P., Vitousek, P.M., Field, C.B., 2008. A unifying framework for dinitrogen fixation in the terrestrial biosphere. *Nature* 454(7202): 327–330.

İslamzade, R., Hasanova, G., Asadova, S., 2023. Impact of varied NPK fertilizer application rates and seed quantities on barley yield and soil nutrient availability in chestnut soil of Azerbaijan. *Eurasian Journal of Soil Science* 12(4): 371 - 381.

Jones, J.B., 2001. Laboratory guide for conducting soil tests and plant analyses. CRC Press, New York, USA. 363p.

Kamzina, G., Seilgazina, S., Suleimenova, S., Zakieva, A., Zhamangarayeva, A., 2022. The effects of NPK fertilization on hay production and some yield components of crested wheatgrass (Agropyron cristatum) in the dry steppe zone of Eastern Kazakhstan. *Eurasian Journal of Soil Science* 11(4): 337-344.

Khan, F, Siddique, A.B., Shabala, S., Zhou, M., Zhao, C., 2023. Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. *Plants* 12(15): 2861.

Li, S., Liu, Z., 2024. Fertilisation and environmental factors affect the yield and quality of alfalfa in China. *Plant, Soil and Environment* 70(5): 276–286.

Liu, H., Li, N., Shen, G., Fu, Y., Wang, X., 2013. Effects of phosphorus fertilizer on the growth and seed yield of alfalfa. *Acta Agrestia Sinca* 21: 571-575.

Liu, M., Zhao, Z., Chen, L., Wang, L., Ji, L., Xiao, Y., 2020. Influences of arbuscular mycorrhizae, phosphorus fertiliser and biochar on alfalfa growth, nutrient status and cadmium uptake. *Ecotoxicology and Environmental Safety* 196: 110537.

Loeppky, H., Horton, P., Bittman, S., Townley-Smith, L., Wright, T., Nuttall, W., 1999. Forage seed yield response to N and P fertilizers and soil nutrients in northeastern Saskatchewan. *Canadian Journal of Soil Science* 79: 265-271.

Macolino, S., Lauriault, L.M., Rimi,F., Ziliotto, U., 2013. Phosphorus and potassium fertilizer effects on alfalfa and soil in a non-limited soil. *Agronomy Journal* 105: 1613–1618.

Madani, H., Stoklosa, A., Zarei, J., Usefi, Z., 2014. Alfalfa (*Medicago sativa* L.) Forage yield responses to triple super phosphate, phosphate solublizing bacteria and gibberllic acid foliar application. *Agronomy* 57: 246–249.

Marschner, H., 1995. Mineral Nutrition of Higher Plants. 2nd Edition. Academic Press. 889p.

Maxotova, A., Nurbayeva, E., Aitbayev, T., Nurgaliyeva, B., 2021. Yield and yield components of five tomato varieties (Solanum lycopersicum) as influenced by chemical NPK fertilizer applications under chestnut soil conditions. *Eurasian Journal of Soil Science* 10(4): 327 - 331.

McLaren, J.R., Buckeridge, K.M., 2019. Decoupled above- and belowground responses to multi-decadal nitrogen and phosphorus amendments in two tundra ecosystems. *Ecosphere* 10(7): e02735.

Medinski, T., Freese, D., Reitz, T., 2018. Changes in soil phosphorus balance and phosphorus-use efficiency under long-term fertilization conducted on agriculturally used Chernozem in Germany. *Canadian Journal of Soil Science* 98: 650-662.

Mehnaz, K.R., Corneo, P.E., Keitel, C., Dijkstra, F.A., 2019. Carbon and phosphorus addition effects on microbial carbon use efficiency, soil organic matter priming, gross nitrogen mineralization and nitrous oxide emission from soil. *Soil Biology and Biochemistry* 134: 175–186.

Meng, X., Chen, W.W., Wang, Y.Y., Huang, Z.R., Ye, X., Chen, L.S., Yang, L.T., 2021. Effects of phosphorus deficiency on the absorption of mineral nutrients, photosynthetic system performance and antioxidant metabolism in Citrus grandis. *PLoS ONE* 16(2): e0246944.

Mori, T., Ohta, S., Ishizuka, S., Konda, R., Wicaksono, A., Heriyanto, J., Hardjono, A., 2013. Effects of phosphorus addition with and without ammonium, nitrate, or glucose on N2O and NO emissions from soil sampled under Acacia mangium plantation and incubated at 100% of the water-filled pore space. *Biology and Fertility of Soils* 49(1): 13–21.

Mori, T., Ohta, S., Ishizuka, S., Konda, R., Wicaksono, A., Heriyanto, J., 2014. Phosphorus application reduces N2O emissions from tropical leguminous plantation soil when phosphorus uptake is occurring. *Biology and Fertility of Soils* 50(1): 45–51.

Muminova, S., Tastanbekova, G., Kashkarov, A., Azhimetova, G., Balgabaev, A., 2022. Effect of foliar mineral fertilizer and plant growth regulator application on seed yield and yield components of soybean (Glycine max) cultivars. *Eurasian Journal of Soil Science* 11(4): 322-328.

Saparov, A., 2014. Soil resources of the Republic of Kazakhstan: Current status, problems and solutions. In: Novel measurement and assessment tools for monitoring and management of land and water resources in agricultural landscapes of Central Asia. Mueller, L., Saparov, A., Lischeid, G. (Eds.). Environmental Science and Engineering. Springer, Cham. pp 61–73.

Scott, J.T., Lambie, S.M., Stevenson, B.A., Schipper, L.A., Parfitt, R.L., McGill, A.C., 2015. Carbon and nitrogen leaching under high and low phosphate fertility pasture with increasing nitrogen inputs. *Agriculture, Ecosystems & Environment* 202: 139–147.

Sengul, S., 2006. Using path analysis to determine lucerne (Medicago sativa L.) seed yield and its components. *New Zealand Journal of Agricultural Research* 49: 107-115.

Stiles, W.A.V., Rowe, E.C., Dennis, P., 2017. Long-term nitrogen and phosphorus enrichment alters vegetation species composition and reduces carbon storage in upland soil. *The Science of the Total Environment* 593–594: 688–694.

Sumner, M.E., Farina, M.P.W., 1986. Phosphorus interactions with other nutrients and lime in field cropping systems. In: Advances in Soil Science. Stewart, B.A. (Ed.). Vol 5. Springer, New York, NY. pp 201–236.

Suwignyo, B., Rini, E. A., Helmiyati, S., 2022. The profile of tropical alfalfa in Indonesia: a review. *Saudi Journal of Biological Sciences* 30: 103504.

Wang, Q., Qin, Z.H., Zhang, W.W., Chen, Y.H., Zhu, P., Peng, C., Wang, L., Zhang, S.X., Colinet, G., 2022. Effect of long-term fertilization on phosphorus fractions in different soil layers and their quantitative relationships with soil properties. *Journal of Integrative Agriculture* 21(9): 2720-2733.

Wang, Z.H., Li, S.X., Malhi, S., 2008. Effects of fertilization and other agronomic measures on nutritional quality of crops. *Journal of the Science of Food and Agriculture* 88(1): 7-23.

Wu, Q.H., Zhang, S.X., Feng, G., Zhu, P., Huang, S.M., Wang, B.R., Xu, M.G., 2020. Determining the optimum range of soil Olsen P for high P use efficiency, crop yield, and soil fertility in three typical cropland soils. *Pedosphere* 30: 832-843.

Xu, L., Tang, G., Wu, D., Zhang, J., 2024. Yield and nutrient composition of forage crops and their effects on soil characteristics of winter fallow paddy in South China. *Frontiers in Plant Science* 14: 1292114.

Yıldız, F., Türk, M., 2015. Effects of phosphorus fertilization on forage yield and quality of common Vetch (Vicia sativa Roth.). *Yuzuncu Yıl University Journal of Agricultural Sciences* 25(2): 134-139.

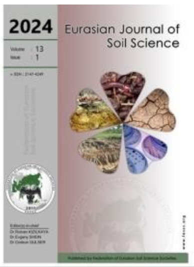
Yu, L., Wang, Y., Zhang, X., Dörsch, P., Mulder, J., 2017. Phosphorus addition mitigates N_2O and CH_4 emissions in N-saturated subtropical forest, SW China. *Biogeosciences* 14(12): 3097–3109.

Zhaksybayeva, G., Balgabayev, A., Vassilina, T., Shibikeyeva, A., Malimbayeva, A., 2022. Yield of sugar beet and changes in phosphorus fractions in relation to long term P fertilization in chestnut soil of Kazakhstan. *Eurasian Journal of Soil Science* 11(1): 25-32.

Eurasian Journal of Soil Science 2024, 13(4), 338 - 347

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



Comparative analysis of lowland rice (*Oryza sativa* L. var. PSB Rc18) performance across different farming systems

Kathlyn L. Quion [a,*], **Berta C. Ratilla** [b]

[a] Agriculture Department, Bohol Island State University, 6317, Bilar, Bohol, Philippines
[b] Department of Agronomy, Visayas State University, 6521, Visca, Baybay City, Leyte, Philippines

Article Info
Received : 08.12.2023
Accepted : 21.07.2024
Available online: 25.07.2024

Author(s)
K.L.Quion *
B.C.Ratilla

* Corresponding author

Abstract

Organic farming is gaining recognition as a viable alternative to conventional methods, promising soil health preservation and sustained crop productivity with economic benefits. This study evaluated the physiological, growth, and yield responses of the PSB Rc18 rice variety and appraised its economic feasibility under different production systems. The experiment was laid out in Randomized Complete Block Design (RCBD) with four replications and three treatments: T1-best bet organic production system, T2-farmers' organic production system in Leyte, and T3-farmers' conventional production system in Leyte. The crop growth rate (CGR) of PSB Rc18 remained consistent across the different systems. However, the Net Assimilation Rate (NAR) peaked significantly between 42-56 days after transplanting (DAT) in the T2. Additionally, the Leaf Area Index (LAI) in T1 was comparable to that of T3. Rice grown under T1 reached heading and maturation earlier than T3. Although T3 produced the highest fresh straw, most productive tillers, and heaviest total biomass, the grain yield was similar across all production systems. Economically, T2 outperformed with a superior benefit-cost ratio of \$0.55 and \$0.94 per USD invested, considering both regular and premium prices for organic palay. These findings highlight organic farming practices' economic and agronomic viability, suggesting that promoting organic farming can be a beneficial alternative to conventional methods in Leyte. This study underscores the potential for integrating organic practices to enhance sustainability and economic outcomes in rice production, making both T1 and T2 significant options for farmers in Eastern Visayas.

Keywords: Organic production systems, physiological response, profitability analysis.

Introduction

Rice (*Oryza sativa* L.) is a critical staple food for 2.7 billion people, predominantly cultivated by several global farmers. Its production exhibits remarkable sustainability and productivity. In comparative terms, irrigated rice boasts significantly higher productivity levels—approximately 100 times more than upland rice, over 12 times more than deep-water rice, and five times more than rainfed rice (Fairhurst and Dobermann, 2002; Mamiit et al., 2021).

In the Philippines, rice serves as the primary food for most Filipinos, yet the total lowland rice cultivation area inadequately caters to the escalating national demands. Eastern Visayas, for instance, allocates only 34% of its land to rice production, yielding an average of 3.44 t ha^{-1}, lower than the national average of 4 t ha^{-1} (PhilRice, 2022). This lower yield is mainly due to the area's susceptibility to tropical storms and ineffective soil and environmental management techniques. Xu et al. (2016) emphasize that enhancing crop management practices to achieve higher productivity, profitability, and environmental sustainability hinges on integrating appropriate nutrient management strategies with agronomic practices.

: https://doi.org/10.18393/ejss.1522102
: https://ejss.fesss.org/10.18393/ejss.1522102
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

However, significant reliance on chemical fertilizers for nutrient management often leads to lower grain yields in intensified rice cropping (Cassman and Pingali, 1995; Patra et al., 2016; Gaurana and Ratilla, 2020). The continual use of chemical fertilizers harms soil health, water sources, and air quality, impacting the soil's physical, chemical, and biological properties (Savci, 2012; Chandini et al., 2019). Surekha et al. (2012) further highlight that conventional fertilizer usage in rice production could lead to long-term soil degradation, adversely impacting productivity.

Organic farming is recognized as a more sustainable option for maintaining soil health and productivity (Surekha and Satishkumar, 2014). Organic production, supported by organic nutrient sources, promotes balanced nutrient release to plants, fostering soil fertility over time (Surekha et al., 2012). While organic farming typically yields less grain than conventional methods (Röös et al., 2018), it proves more resilient to extreme weather conditions such as drought, flooding, or waterlogging (Wani et al., 2013; Heckelman et al., 2018). While historical data may suggest that organic cropping systems are less profitable than conventional systems (Dobbs and Smolik, 1977), recent findings assert that organic farming can be more profitable (Crowder and Reganold, 2015; Reganold and Wachter, 2016; Gaurana and Ratilla, 2020).

Despite the potential benefits, the specific effects of organic farming on the physiological, growth, and yield responses of rice varieties in Eastern Visayas are not well-documented. Additionally, there is limited information on the economic feasibility of organic farming practices in this region. Understanding physiological parameters such as leaf area index (LAI), net assimilation rate (NAR), and crop growth rate (CGR) associated with different production systems is imperative to identify the factors limiting the yield of lowland rice. Elevated yield directly correlates with increased dry matter production (Peng et al., 1999; Hasegawa, 2003). Nevertheless, dry matter production varies based on genotype, environmental conditions, and cultivation practices (Quang Duy et al., 2004).

This study aims to fill this gap by evaluating the physiological, growth, and yield responses of the PSB Rc18 rice variety under different production systems. Specifically, it investigates how organic and conventional farming practices affect these parameters and their economic feasibility. By addressing these aspects, the study seeks to provide insights into the viability of organic farming as an alternative to conventional methods in the Philippines, particularly in regions like Eastern Visayas. This research aims to assess the impact of different production systems on the CGR, NAR, LAI, and growth and yield performance of PSB Rc18 and to analyze the economic benefits of organic and conventional farming practices.

Material and Methods

The research took place at the experimental area of the Department of Agronomy, Visayas State University, Visca, Baybay City, Leyte, Philippines (10º44’45’’N 124º47’33’’E) from August to December 2017. Before planting, a comprehensive soil analysis was undertaken, considering the preceding cropping. Soil samples per treatment per replication were collected from the experimental area before land preparation at a 0-20 cm depth.

These samples were air-dried, pulverized, and sieved using 2.0 mm wire mesh and were submitted for the analysis of soil pH (1:2.5 soil water ratio; ISRIC 1995), organic matter content (%) (Modified Walkley Black Method, PCARR 1980), total N (%) (Modified Kjeldahl Method, Nelson and Sommers, 1982), available P (mg kg^{-1}) (Modified Olsen Method, Olsen et al., 1954) and exchangeable K (meq/100 g) (Ammonium Acetate Method, ISRIC 1995) at the Central Analytical Services Laboratory (CASL), PhilRootCrops, VSU, Visca, Baybay City, Leyte, Philippines. Specifically, the soil displayed a range of pH levels from strongly acidic to very strongly acidic, deficient %OM and %OC, and low available P. However, the total N content and exchangeable K exhibited a medium amount based on Landon (1991) indices.

For the final soil analysis, three soil samples were collected after harvesting from each treatment plot in every replication. These were processed and analyzed for the same aforementioned soil parameters.

Experimental Design and Treatments

The experiment was laid out in RCBD with four replications. Each block was subdivided into three plots measuring 5 m x 6 m with 2 m alleyways between replications and treatment plots. Treatments are as follows:

T1 : best bet organic production system (green leaf manuring + vermicast [37.26–508.25–13.07 kg N, P_2O_5, K_2O ha^{-1}] + vermitea [0.06–4.87–0.32 L N, P_2O_5, K_2O ha^{-1}] + fermented plant juice [0.94–23.70–7.02 L N, P_2O_5, K_2O ha^{-1}] + fermented fruit juice [0.67–3.42–39.06 L N, P_2O_5, K_2O ha^{-1})

T2 : organic farmers' practice in Leyte (vermicast [10.35–141.18–3.63 kg N, P_2O_5, K_2O ha^{-1}] + vermitea [0.04–3.13–0.21 L N, P_2O_5, K_2O ha^{-1}] + fermented plant juice [0.35–8.88–2.63 L N, P_2O_5, K_2O ha^{-1}] + fermented fruit juice [0.67–3.42–39.60 L N, P_2O_5, K_2O ha^{-1}]

T3 : conventional farmers' practice in Leyte (109.04–17.5–17.5 kg N, P_2O_5, K_2O ha^{-1})

The organic fertilizers employed in this research underwent nutrient analysis at the Central Analytical Services Laboratory (CASL), PhilRootCrops, VSU, Visca, Baybay City, Leyte, Philippines, to determine the pH, total N, P, K, and moisture content (MC). The pH, total N (%), and MC (%) were analyzed using the same methods for soil analysis. The total P (%) was determined using the Vanadomolybdate Method, and the total K (%) was measured using Flame Atomic Emission Spectroscopy (FAES) following the protocols outlined by the Bureau of Soils and Water Management (BSWM, 2014). The nutrient analysis results (Table 1) unveiled distinctive characteristics among the different organic fertilizers. Vermicast had a near-neutral pH of 6.83, while Fermented Plant Juice (FPJ) was the most acidic (pH 4.20). Furthermore, vermicast demonstrated the highest levels of total nitrogen (0.69%) and phosphorus (4.11%), while Fermented Fruit Juice (FFJ) recorded the highest potassium content at 18.18%. Among the utilized nutrient sources, vermicast underscores the potential for supplying nutrients beneficial for rice crops.

Table 1. pH, organic matter, total N, P, K, and % MC of nutrient sources

Fertilizers	pH (1:2.5)	OM (%)	Total N (%)	Total P (%)	Total K (%)	MC (%)
Vermicast	6.83	10.34	0.69	4.11	0.20	69.16
Vermitea	4.53		0.02	0.73	0.09	
Fermented Fruit Juice (FFJ)	4.60		0.37	0.83	18.18	
Fermented Plant Juice (FPJ)	4.20		0.19	2.07	1.16	

Source: Central Analytical Services Laboratory, PhilRootcrops, Visayas State University, Visca, Baybay City, Leyte, Philippines

Before the commencement of the experiment, plots identified under T1 received an application of kakawate *(Gliricidia sepium)* as green leaf manure, applied at a rate of 2 kg m^{-2} and incorporated into the soil before final land preparation. This was allowed to decompose for two weeks before transplanting. In contrast, T3 was administered with inorganic fertilizers at a rate of 109.04-17.5-17.5 kg N, P_2O_5, K_2O ha^{-1}. This involved a basal application comprising a mixture of 125 kg ha^{-1} complete fertilizer combined with 79 kg ha^{-1} urea, split into two applications—one given a week after transplanting and the other 15 days later. Following this, urea was top-dressed at a rate of 120 kg ha^{-1} during panicle initiation, which was identified through a visual examination of the furry tip at the center of the stem. The fertilizers applied were incorporated into the soil after application.

On the other hand, plots assigned to T1 and T2 received vermicast applications at rates of 5 t ha^{-1} and 1.5 t ha^{-1}, respectively, before the transplanting. Fermented Plant Juice (FPJ), FFJ, and vermitea were employed in T1 and T2 treatments for foliar spray applications. Treatment 1 received weekly applications of vermitea and alternated with a 10% FPJ solution starting from one week after transplanting and continuing up to the flowering stage, administered at a rate of 291.66 L ha^{-1} vermitea and 500 L ha^{-1} for FPJ. Conversely, T2 was sprayed weekly with a combination of FPJ and vermitea, with a total volume of 375 L ha^{-1}, starting two weeks after the transplanting until the heading stage. At the panicle initiation phase, FFJ was sprayed in T1 and T2 two weeks before harvest. The foliar fertilizers were applied late afternoon, between 4:00-5:00 pm.

Rice Establishment and Maintenance

Lowland rice seedlings were raised using the wet bed method wherein PSB Rc18 seeds weighing 480 g per treatment were soaked in tap water for 24 hours and incubated for 36 hours. Pre-germinated seeds for T1 were sown in a prepared seedbed enriched with 1 kg m^{-2} of vermicast. After 21 days, these seedlings were transplanted at a distance of 20 cm x 20 cm. A day after transplanting (DAT), myko plus was drenched in T1 at 100 g 16 L^{-1} of water. Replanting was performed five days after transplanting to replace missing hills and maintain the desired population of 750 hills per plot.

At 5 DAT, the experimental area was irrigated with water to a depth of 2.5 cm. However, during rainy periods, the water source for irrigation was temporarily closed to prevent excessive flooding. The field was drained with water two weeks before harvest to promote maturity and facilitate harvesting. Rotary weeding was performed at 14 DAT, and hand weeding was carried out five days later to manage weeds around the hills. Subsequently, weeds in dikes were controlled by under-brushing using a sharp sickle. Pests and disease incidence in the T1 and T2 treatments were addressed by applying panyawan (*Tinospora rumphii*) extracts.

In the case of T3, karate (lambda-cyhalothrin) was sprayed at a rate of 30 mL 16 L^{-1} of water to control rice stink bugs (*Oebalus pugnax*) during the vegetative and flowering stages at intervals of 10 days. During the heading stage, lannate (methomyl insecticide) was sprayed at a rate of 30 mL 16 L^{-1} of water to manage rice bugs (*Leptocorisa oratorius*). During the spraying process, a plastic enclosure was employed around the conventional treatment plots to prevent contamination of spray mists with other treatments. Harvesting was done when 85% of the grains within the panicles had ripened. The harvested grains were threshed, cleaned, and sun-dried to 14% MC before weighing.

Data gathered

Three soil samples were gathered from each treatment plot within each replication upon harvest to assess potential changes in soil properties following the application of specified treatments. These samples were analyzed for parameters such as soil pH, % OM, total N, available P, and exchangeable K. For the lowland rice crops, the collected data encompassed both physiological parameters, including Net Assimilation Rate (NAR), Crop Growth Rate (CGR), and Leaf Area Index (LAI), and agronomic characteristics, which is the number of days from sowing to heading and maturity, plant height (cm) and fresh straw yield (t ha^{-1}). The yield and yield components were the numbers of productive tillers per hill, filled and unfilled grains per panicle, percentage of filled spikelets per panicle, weight of 1000 grains (g), panicle length (cm), grain yield (t ha^{-1}) and total biomass (t ha^{-1}). The Harvest Index, a measure of plant productivity, was computed by dividing the economic yield (grains) by the biological yield. To ensure accuracy, both grains and the herbage from three sample plants in each treatment were subjected to oven-drying at 70°C for 72 h before weighing.

A profitability analysis aggregated all expenses incurred during the study, from land preparation to harvesting. These costs were then subtracted from the gross income. Additionally, net return and the benefit-cost ratio were calculated as part of the analysis.

Meteorological data, including total weekly rainfall, minimum and maximum temperatures, and relative humidity throughout the study, were sourced from the Philippine Atmospheric Geophysical and Astronomical Services Station, Visayas State University, Visca, Baybay City, Leyte.

Statistical analysis

The consolidated data were analyzed using Statistical Analysis Software (SAS) Version 9.2 developed by SAS Institute. Significant means were compared using Tukey's Honestly Significant Difference (HSD) test.

Results and Discussion

Soil characteristics

The findings from the final soil analysis indicated that most soil parameters were similar across various production systems, except exchangeable K. Notably, at a depth of 20 cm, the exchangeable K levels in T1 and T2 were significantly higher compared to T3. This increase could be linked to the higher turnover of rice straw and residues from previous crop cycles (Table 2). Rice straw contains a substantial amount of potassium (Dobermann and Fairhurst, 2002), and for this potassium to become available, soil microorganisms need to decompose the residues. In contrast to the inorganic plots (T3), the organic plots (T1 and T2) received organic fertilizers like vermicast, vermitea, FFJ, and FPJ, potentially enhancing the soil's microbial population. This suggests that the organic plots (T1 and T2) retained more available nutrients from the added crop residues.

Table 2. Soil analysis of the experimental area before and after the conduct of the study

Treatment	pH (1:2.5)	SOM (%)	SOC (%)	Total N (%)	Avail. P (mg/kg)	Exch. K (meq/100g)
Before Planting						
T1 = Best bet organic production system	5.08	2.97	1.73	0.34	6.51	0.50
T2 = Organic farmers' practice in Leyte	5.05	2.82	1.64	0.28	8.63	0.39
T3 = Conventional farmers' practice in Leyte	4.91	2.81	1.64	0.27	7.43	0.35
CV (%)	4.77	5.03	5.03	27.97	29.11	33.01
After Planting						
T1 = Best bet organic production system	5.13	2.66	1.55	0.21	7.10	0.36^{a}
T2 = Organic farmers' practice in Leyte	5.15	2.56	1.49	0.16	5.21	0.34^{ab}
T3 = Conventional farmers' practice in Leyte	5.09	2.43	1.41	0.16	4.93	0.19^{b}
CV (%)	1.07	11.34	11.34	20.42	25.88	24.58

Treatment means within a column without a letter or followed by a common letter(s) are not significantly different at a 5% level of significance using HSD

Physiological Response

Figure 1 reveals that the various production methods influenced the NAR of rice, specifically between 42-56 DAT, whereas the CGR did not differ significantly. Nevertheless, numerical data showed increased CGR from 14-56 DAT, followed by a decline as the crop matured due to some senescence. This trend parallels the findings of Itang (2014) and Abit (2016), indicating that the increase in CGR during the vegetative stage of rice was associated with an increased leaf area, allowing for more effective light interception, thereby augmenting photosynthetic rates and the production of dry matter. As leaves aged and were shed, there was a noticeable decline in CGR at 60-90 DAT (Mehta et al., 2013). The highest NAR value recorded between 42-56 DAT in rice grown under T2 may be linked to its upright leaf canopy. Conversely, vigorous growth in T1 and T3 led to mutual shading among rice plants, potentially contributing to their lower NAR values. Consequently, the reduced shading in T2 likely facilitated more efficient photosynthetic activity.

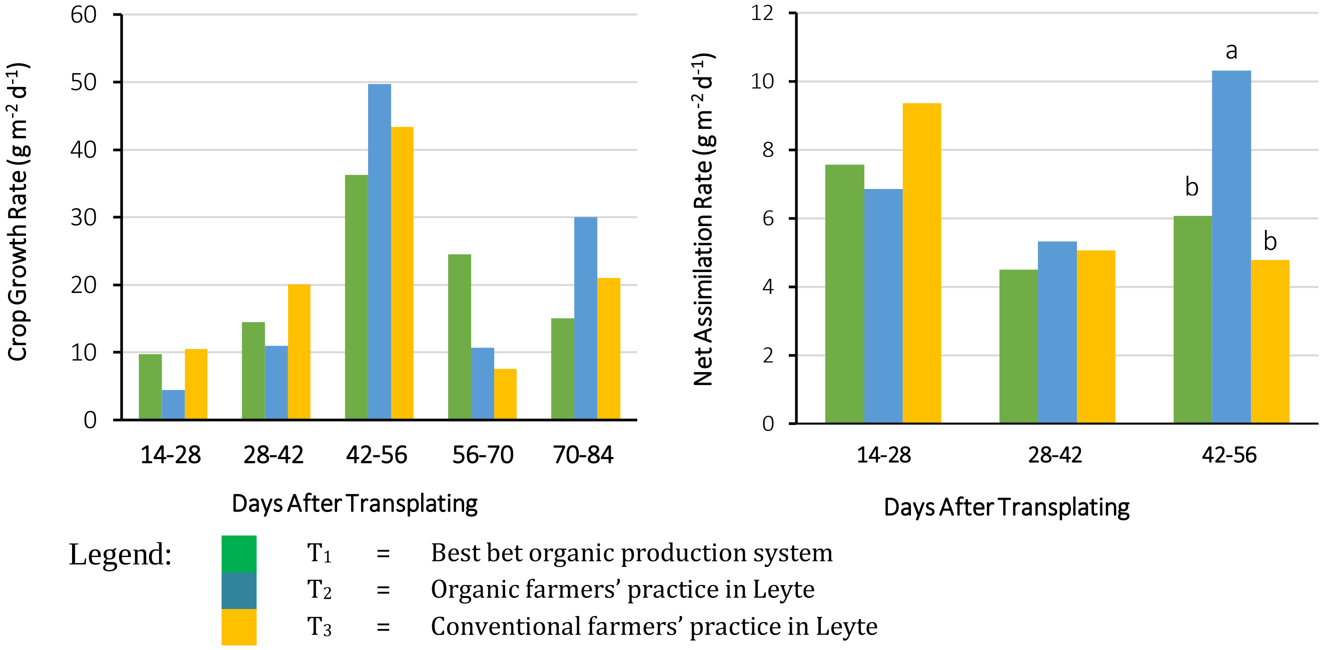


Figure 1. Physiological characteristics of lowland rice (PSB Rc18) under different production systems

Agronomic Response

The study results indicated significant differences in the days to heading and maturity, leaf area index (LAI), fresh straw yield, and total biomass (Table 3). Notably, rice plants in T1 exhibited an earlier heading and maturation than those in T3. This result aligns with research by Gaurana and Ratilla (2020), which found that organic fertilizer application led to earlier heading and maturity compared to inorganic fertilizers. Treatments 1 and 3 recorded higher LAI values than T2, likely due to more significant N application in the former two production systems. The nutrient analysis (Table 1) reveals that T1 and T3 received relatively higher N inputs than T2. The higher LAI in T1 may have been influenced by the incorporation of kakawate (*G. sepium*) as green leaf manure, the addition of vermicast, and weekly foliar spraying of fermented plant juice (FPJ), which supplied substantial N, resulting in larger and broader leaves. Similarly, the application of 109.04 kg ha^{-1} of nitrogen in T3 contributed to the elevated LAI values, consistent with the findings of Vaesen et al. (2001) that increased nitrogen application positively impacted the LAI of lowland rice.

Table 3. Days from sowing to heading and maturity, plant height, leaf area index, fresh straw yield and total biomass of lowland rice (PSB Rc18) under different production systems

Treatments	Days from sowing to		Plant Height (cm)	Leaf Area Index	Fresh Straw Yield (t/ha)	Total biomass (t/ha)
	Heading	Maturity				
T_1 = Best bet organic production system	83.00^{c}	126.00^{b}	110.58	5.66^{ab}	22.02^{b}	24.95^{b}
T_2 = Organic farmers' practice in Leyte	88.00^{b}	126.00^{b}	102.53	3.64^{b}	19.40^{b}	21.84^{c}
T_3 = Conventional farmers' practice in Leyte	89.00^{a}	133.00^{a}	114.13	8.50^{a}	29.20^{a}	31.29^{a}
CV (%)	0.00	0.00	7.40	23.80	5.86	4.38

Treatment means within a column without a letter or followed by a common letter(s) are not significantly different at a 5% level of significance using HSD

In contrast, T3 exhibited a notably higher fresh straw yield and total biomass among the different production systems, likely due to the rapid conversion of urea into readily available N for rice plants. This differs from organic amendments, where a significant portion of the N is released after mineralization (Dash et al., 2011). Treatments 1 and 2, which rely on organic fertilizers, contained lower N amounts, approximately 37.26 kg and 10.35 kg ha^{-1}, along with 1.67 L ha^{-1} and 1.06 L ha^{-1} from foliar supplements, respectively, in comparison to T3, which received 109.04 kg N ha^{-1}. Similar findings have been reported by Mannan et al. (2010) and Cagasan and Tamayo (2016), emphasizing that higher N rates significantly increase the fresh straw yield of lowland rice. This increased fresh straw yield in T3 also translated into higher total biomass, in line with the results obtained by Gaurana and Ratilla (2020) and Dela Peña (2017). Among the parameters related to yield and yield components assessed, the number of productive tillers and panicle length significantly varied among the production systems (Table 4 and 5). Treatment 3 yielded the highest number of productive tillers, followed by T1. This result is consistent with the findings of Cagasan and Tamayo (2016), demonstrating that inorganic fertilizer application resulted in increased tiller production. Additionally, longer panicles were observed in both T1 and T3, likely due to the higher N supply. Nitrogen was found to substantially influence panicle formation and elongation, consistent with Pramanik and Bera (2013) and Gaurana and Ratilla (2020).

Table 4. Number of productive tillers, filled and unfilled grains, and percent filled grains per panicle of lowland rice (PSB Rc18) under different production systems

Treatments	No. of productive tillers	No. of grains per panicle		Percent filled spikelet per panicle
		Filled	Unfilled	
T_1 = Best bet organic production system	15.50^b	100.75	63.00	61.45
T_2 = Organic farmers' practice in Leyte	11.50^c	93.50	48.73	65.58
T_3 = Conventional farmers' practice in Leyte	18.00^a	80.75	60.05	57.51
CV (%)	5.88	11.25	19.31	9.19

Treatment means within a column without a letter or followed by a common letter(s) are not significantly different at a 5% level of significance using HSD

Table 5. Panicle length, weight of 1000 grains, grain yield, and harvest index of lowland rice (PSB Rc18) under different production systems

Treatments	Panicle length (cm)	Weight of 1000 grains (g)	Grain yield (t/ha)	Harvest index
T_1 = Best bet organic production system	25.42^a	23.22	2.93	0.35
T_2 = Organic farmers' practice in Leyte	23.48^b	23.91	2.44	0.36
T_3 = Conventional farmers' practice in Leyte	25.45^a	22.55	2.09	0.27
CV (%)	2.63	3.89	18.91	16.09

Treatment means within a column without a letter or followed by a common letter(s) are not significantly different at a 5% level of significance using HSD

Despite T1 and T3 displaying longer panicles, there were no significant differences in grain yield across the various production systems. This may be due to the compensatory effects of comparable 1000-grain weight, number of filled grains, percentage of filled spikelets per panicle, and harvest index, among other factors. Despite T1 and T3 receiving relatively higher nutrient inputs, T2 utilized its available nutrients more efficiently. However, it is imperative to acknowledge the external factors contributing to the observed reduction in grain yield. Notably, the influence of three tropical storms during the heading and grain-filling stages underscores the susceptibility of rice crops to adverse weather conditions (Yoshida, 1981). Moreover, the residual crop from the previous cultivation could have depleted soil nutrients, given that no amendments were added to the prior crop. Residual cropping can consume available nutrients in the soil through nutrient mining (Syers, 1997). However, continuous application of organic amendments may increase grain yield in lowland rice production.

Profitability analysis

In this study, the net income recorded lower values than the preceding five croppings (Table 6 and 7). This decline might be attributed to the impact of tropical storms occurring during critical growth stages heading and grain-filling stages. However, despite this, all production systems remained profitable, recovering their production costs. Considering the current market price of \$0.34 kg^{-1} of ordinary palay in the locality, T2 achieved the highest net return of \$296 ha^{-1}, with the most favorable benefit-cost ratio of USD 0.55. Following T2, T3 acquired a net return of \$217 ha^{-1}, with a benefit-cost ratio of USD 0.44. Even though T1 obtained the highest grain yield, it incurred more significant production costs due to expensive vermicast, resulting in a lower net return of \$20 ha^{-1} and a benefit-cost ratio of USD 0.02.

Table 6. Cost and return analysis of lowland rice (PSB Rc18) under different production systems following the price of ordinary rice

Treatments	Grain yield (t/ha)	Gross Income** (USD/ha)	Production Cost (USD/ha)	Net Income (USD/ha)	Benefit Cost Ratio (USD)	Break Even Yield (kg/ha)
T_1 = Best bet organic production system	2.93	996	976	20	0.02	2,870.55
T_2 = Organic farmers' practice in Leyte	2.44	830	534	296	0.55	1,570.55
T_3 = Conventional farmers' practice in Leyte	2.09	711	494	217	0.44	1,451.85
Mean	2.49	845	668	178	0.34	1,964.32

**Based on the price of unmilled rice at farm gate price at $0.34/kg

Table 7. Cost and return analysis of lowland rice (PSB Rc18) under different production systems following the premium price for organic rice

Treatments	Grain Yield (t/ha)	Gross Income** (USD/ha)	Production Cost (USD/ha)	Net Income (USD/ha)	Benefit Cost Ratio (USD)	Break Even Yield (kg/ha)
T1 = Best bet organic production system	2.93	1,245	976	269	0.28	2,296.44
T2 = Organic farmers' practice in Leyte	2.44	1037	534	503	0.94	1,256.44
T3 = Conventional farmers' practice in Leyte	2.09	711	494	217	0.44	1,451.85
Mean	2.49	998	668	330	0.55	1,668.24

**Based on the price of unmilled organic rice at $0.43/kg (T1 and T2)

However, considering the potential sale of organic rice at a premium price of \$0.43 kg^{-1}, T2 continued to exhibit the highest net return of \$503 ha^{-1} and a cost-benefit ratio of USD 0.94. T1 also generated a net return of \$269 ha^{-1} with a cost-benefit ratio of USD 0.28, surpassing the net return of T3. Through assessments based on break-even yield, net income, and benefit-cost ratios, all three production systems exhibited the capability to recover their production costs under adverse climatic conditions. Nevertheless, when exposed to adverse conditions, T2 demonstrated relative practicality, profitability, and resilience advantages. Despite T1 achieving a relatively high grain yield in unfavorable conditions, its higher production costs did not equate to increased net returns. Consequently, these results suggest that T2 represents a potential option capable of competing with T3, albeit highlighting the need to optimize its nutrient application further. Furthermore, multiple researchers have highlighted the benefits of organic rice farming, including energy efficiency (Mendoza, 2004), improvements in soil physical, fertility, and biological properties (Ramesh et al., 2010), enhanced adaptive capacity, mitigation potential, reduced vulnerability (Heckelman et al., 2018), and assurance of food safety for consumers and producers (Sirieix, 2011; EFIC, 2013).

Meteorological data

Figure 2 illustrates the total rainfall accumulation throughout the experimental period, amounting to 2,255.50 mm. The highest recorded rainfall was documented during week 17, reaching 556.60 mm, followed by week 9 with 441.30 mm, while the lowest rainfall occurred during week 2, with 25.40 mm. The substantial increase in rainfall during weeks 9 and 17 can be attributed to the influence of tropical storms "Lan," "Kai-tak," and "Tembin." As per established standards, the total water requirement for rice typically stands at approximately 1,200 mm (Yoshida, 1981). Week 9, identified as the early vegetative stage in this study, experienced continuous rainfall. Yu et al. (2016) highlighted that prolonged rainy periods during this stage adversely impact the tillering stage, ultimately resulting in reduced grain yields. Conversely, week 17 marked the milking and dough stages, in which strong winds accompanying tropical storms "Kai-tak" and "Tembin" led to lodging and grain shattering.

An interesting observation among the production systems was that 50% of the rice plants in T3 experienced lodging at an angle of 60^0. In contrast, all rice plants in the organic treatments (T1 and T2) remained upright. This finding suggests that rice plants cultivated under organic production systems exhibit greater resilience to adverse weather conditions, such as tropical storms. This aligns with the findings of Heckelman et al. (2018), emphasizing that paddy rice grown under organic systems demonstrates enhanced climate resilience compared to conventional methods.

On the other hand, the recorded minimum and maximum air temperatures fluctuated between 21-27.50^{0}C and 27.50-35.80^{0}C, respectively. These temperatures conformed to the optimum requirement of growing paddy rice for average growth and development, which ranges from 25-35^{0}C (Shimono et al., 2002). Additionally, the relative humidity levels throughout the study period ranged from 78.50% to 92.42%, consistently within the required range for paddy rice cultivation.

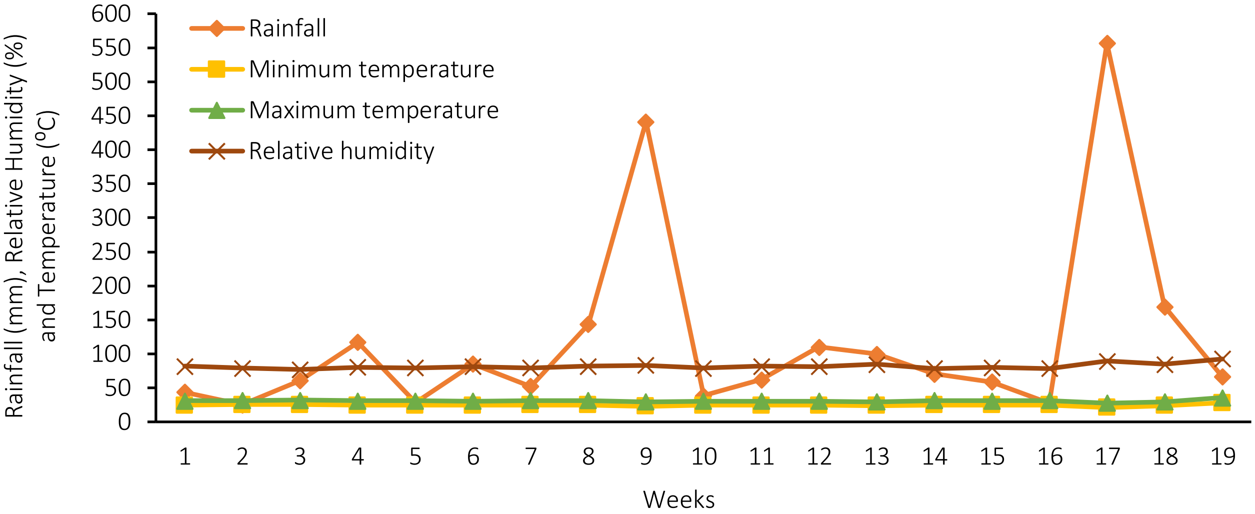


Figure 2. Total weekly rainfall, average weekly minimum and maximum temperature and relative humidity during the conduct of the study (August 21 - December 30, 2017)

Conclusion

The crop growth rate (CGR) remained consistent across all systems, while the organic system in Leyte (T2) demonstrated the highest net assimilation rate (NAR) between 45-56 days after transplanting (DAT). The leaf area index (LAI) in the optimal organic system (T1) was comparable to that of the conventional system (T3), which, despite having more productive tillers and higher total biomass, produced a grain yield similar to that of other systems. Economically, all systems were profitable, but T2 achieved a superior benefit-cost ratio, with $0.55 and $0.94 per USD invested at regular and premium organic palay prices, respectively. These results align with existing literature suggesting that organic farming can yield comparable results to conventional methods while enhancing economic returns and sustainability. However, the study's focus on a single rice variety and specific regions may limit generalizability, highlighting the need for further research on different varieties and regions. Despite these limitations, the study underscores the potential of organic farming practices to provide significant economic and environmental benefits, promoting their broader adoption in agricultural practices.

Acknowledgement

The primary author extends sincere thanks to the Department of Agronomy at Visayas State University and the Department of Science and Technology-Science Education Institute (DOST-SEI) of the Republic of the Philippines for the scholarship award granted through the Accelerated Science and Technology Human Resource Development Program (ASTHRDP), which enabled the conduct of this study.

References

Abit, G., 2016. Growth and yield of lowland rice (*Oryza Sativa* L.) as influenced by different nutrient management and tillage practices under a zero synthetic pesticide production system. MS Thesis. Visayas State University, Department of Agronomy, Leyte, Philippines. 14-15 pp.

BSWM, 2014. Updated manual for soil, water, plant tissue and fertilizer analysis. Department of Agriculture. Laboratory Service Division. Bureau of Soils and Water Management (BSWM)

Cagasan, U.A., Tamayo, N.V., 2016. Growth and yield performance of ırrigated lowland Rice NSIC Rc218 (L.) as ınfluenced by oryza sativa water and fertilizer applications. *Annals of Tropical Research* 38(2): 83-95.

Cassman, K.G., Pingali, P.L., 1995. Intensification of irrigated rice systems: learning from the past to meet future challenges. *GeoJournal* 35: 299-305.

Chandini, Kumar, R., Kumar, R., Prakash, O., 2019. The impact of chemical fertilizers on our environment and ecosystem. In: Research Trends in Environmental Sciences. pp. 71-85.

Crowder, D.W., Reganold, J.P., 2015. Financial competitiveness of organic agriculture on a global scale. *Proceedings of the National Academy of Sciences (PNAS)* 112(24): 7611-7616.

Dash, D., Patro, H., Tiwari, R.C., Shahid, M., 2011. Effect of organic and inorganic sources of N on growth attributes, grain and straw yield of rice (Oryza sativa). *International Journal of Pharmaceutical and Life Sciences* 2(4): 655-660.

Dela Peňa, W.R., 2017. Organic production systems' effects on the performance, pest, natural enemies and sensory qualities of lowland rice (*Oryza sativa* L. var PSB Rc18) MS Thesis. Visayas State University, Department of Agronomy, Leyte, Philippines. pp. 43-54.

Dobbs, T.L., Smolik, J.D., 1997. Productivity and profitability of conventional and alternative farming systems: A long-term on-farm paired comparison. *Journal of Sustainable Agriculture* 9(1): 63-79.

Dobermann, A., Fairhurst, T., 2000. Rice: Nutrient Disorders and Nutrient Management. International Rice Research Institute, Philippines. 162p.

EFIC, 2013. Organic food and farming: Scientific facts and consumer perceptions. European Food Information Council. Available at [Access date: 08.12.2023]: https://www.eufic.org/en/food-production/article/organic-food-and-farming-scientific-facts-and-consumer-perceptions

Fairhurst, T., Dobermann, A., 2002. Rice in the global food supply. Available at [Access date: 08.12.2023]: http://www.ipni.net/publication/bci.nsf/0/42A2EA40E95CBD1385257BBA006531E9/$FILE/Better%20Crops%20International%202002-3%20p03.pdf

Gaurana, M.L., Ratilla, B.C., 2020. Agronomic response, nutrient uptake, and profitability of PSB Rc18 lowland rice under organic production systems. *Philippine Journal of Crop Science* 45(1): 46-55.

Hasegawa, H., 2003. High-yielding rice cultivars perform best even at reduced nitrogen fertilizer rate. *Crop Science* 43(3): 921-926.

Heckelman, A., Smukler, S., Wittman, H., 2018. Cultivating climate resilience: a participatory assessment of organic and conventional rice systems in the Philippines. *Renewable Agriculture and Food Systems* 33(3): 225-237.

ISRIC, 1995. Procedures for soil analysis. Van Reuwijk, L.P. (Ed.). International soil reference and information center Wageningen, the Netherlands. 106p.

Itang, M.F., 2014. Morphological and agronomic responses of submergence and drought-tolerant lowland rice varieties to different plant spacing and water management. MS Thesis. Visayas State University, Department of Agronomy, Leyte, Philippines. 36-38 pp.

Landon, J.R., 1991. Booker tropical soil manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. Longman Scientific and Technical, Essex, New York. 474p.

Mamiit, R.J., Yanagida, J., Miura, T., 2021. Productivity hot spots and cold spots: setting geographic priorities for achieving food production targets. *Frontiers in Sustainable Food Systems* 5: 727484.

Mannan, M.A., Bhuiya, M.S.U., Hossain, H.M.A., Akhand, M.I.M., 2010. Optimization of nitrogen rate for aromatic Basmati rice (*Oriza sativa* L.). *Bangladesh Journal of Agricultural Research* 35(1): 157-165.

Mehta, M.K., Reddy, S.N., Sankar, A.S., Raju, C.S., 2013. A study on physiological attributes and yield in aromatic rice during Kharif season. *International Journal of Agricultural Sciences* 9(2): 504-509.

Mendoza, T.C., 2004. Evaluating the benefits of organic farming in rice agroecosystems in the Philippines. *Journal of Sustainable Agriculture* 24(2): 93-115.

Nelson, D.W., Sommers, L.E., 1996. Total carbon organic carbon and organic matter. In: Methods of Soil Analysis: Part 3 Chemical Methods, 5.3. Sparks, D.L. Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.). SSSA Book Series No. 5. ASA-SSSA Madison WI, USA, pp. 961–1010.

Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. U.S. Department of Agriculture, Circular No 939, USA, 19p.

Patra, S., Mishra, P., Mahapatra, S.C., Mithun, S.K., 2016. Modelling impacts of chemical fertilizer on agricultural production: a case study on Hooghly district, West Bengal, India. *Modeling Earth Systems and Environment* 2: 1-11.

PCARR, 1980. A standard method of analysis for soil, plant tissue water, and fertilizer. Los Baňos (Laguna): Farm, Resource, and Systems Research Division, Philippine Council for Agriculture and Research, 194 p.

Peng, S., Cassman, K.G., Virmani, S.S., Sheehy, J., Khush, G.S., 1999. Yield potential trends of tropical rice since the release of IR8 and the challenge of increasing rice yield potential. *Crop Science* 39(6): 1552-1559.

PhilRice, 2002. State of the Rice Sector in the Eastern Visayas. Philippine Rice Institute. Available at [Access date: 08.12.2023]: https://www.philrice.gov.ph/ricelytics/main/region/8

Pramanik, K., Bera, A.K., 2013. Effect of seedling age and nitrogen fertilizer on growth, chlorophyll content, yield and economics of hybrid rice (Oryza sativa L.). *International Journal of Agronomy and Plant Production* 4(5): 3489-3499.

Quang Duy, P., Hirano, M., Sagawa, S., Kuroda, E., 2004. Analysis of the dry matter production process related to yield and yield components of rice plants grown under the practice of nitrogen-free basal dressing accompanied with sparse planting density. *Plant Production Science* 7(2): 155-164.

Ramesh, P., Panwar, N.R., Singh, A. B., Ramana, S., Yadav, S.K., Shrivastava, R., Rao, A.S., 2010. Status of organic farming in India. *Current Science* 98(9): 1190-1194.

Reganold, J.P., Wachter, J.M., 2016. Organic agriculture in the twenty-first century. *Nature Plants* 2(2): 1-8.

Röös, E., Mie, A., Wivstad, M., Salomon, E., Johansson, B., Gunnarsson, S., Watson, C.A., 2018. Risks and opportunities of increasing yields in organic farming. A review. *Agronomy for Sustainable Development* 38: 1-21.

Savci, S., 2012. Investigation of effect of chemical fertilizers on environment. *APCBEE Procedia* 1: 287-292.

Shimono, H., Hasegawa, T., Iwama, K., 2002. Response of growth and grain yield in paddy rice to cool water at different growth stages. *Field Crops Research 73*(2-3): 67-79.

Sirieix, L., Kledal, P.R., Sulitang, T., 2011. Organic food consumers' trade-offs between local or imported, conventional or organic products: a qualitative study in Shanghai. *International Journal of Consumer Studies* 35(6): 670-678.

Surekha, K., Rao, K.V., Shobha Rani, N., Latha, P.C., Kumar, R.M., 2012. Evaluation of organic and conventional rice production systems for their productivity, profitability, grain quality and soil health. International Conferences on "Agricultural & Horticultural Sciences". Agrotechnol 2012, 1:2. 14-15 September 2012. India.

Surekha, K., Satishkumar, Y.S., 2014. Productivity, nutrient balance, soil quality, and sustainability of rice (*Oryza sativa* L.) under organic and conventional production systems. *Communications in Soil Science and Plant Analysis* 45(4): 415-428.

Syers, J.K., 1997. Managing soils for long-term productivity. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* 352(1356): 1011-1021.

Vaesen, K., Gilliams, S., Nackaerts, K., Coppin, P., 2001. Ground-measured spectral signatures as indicators of ground cover and leaf area index: the case of paddy rice. *Field Crops Research* 69(1): 13-25.

Wani, S.A., Chand, S., Najar, G.R., Teli, M.A., 2013. Organic farming: As a climate change adaptation and mitigation strategy. *Current Agriculture Research Journal* 1(1): 45-50.

Xu, X., He, P., Zhao, S., Qiu, S., Johnston, A.M., Zhou, W., 2016. Quantification of yield gap and nutrient use efficiency of irrigated rice in China. *Field Crops Research* 186: 58-65.

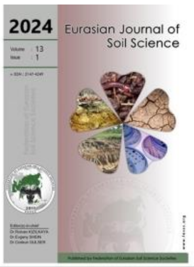
Yoshida, S., 1981. Fundamentals of Rice Crop Science, International Rice Research Institute, Los Baños.

Yu, W., Wang, Y., Li, D., Xu, S., Abdul-Gafar, A., 2016. Could rice yield change be caused by weather?. *Journal of Agricultural Chemistry and Environment* 5(1): 31-37.

Eurasian Journal of Soil Science 2024, 13(4), 348 - 357

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



Phytoremediation of contaminated urban soils spiked with heavy metals

Bakhytzhan K. Yelikbayev [a], **Fatima Imanbek** [a], **Gulya A. Jamalova** [a],
Nicolas E. Kalogerakis [b], **K. Rafiq Islam** [c,*]

[a] Satbayev University, Almaty, Kazakhstan
[b] Technical University of Crete, Chania, Greece
[c] The Ohio State University South Centers, Piketon, Ohio, USA

Article Info

Received : 11.03.2024
Accepted : 21.07.2024
Available online: 25.07.2024

Author(s)

B.K.Yelikbayev
F.Imanbek
G.A.Jamalova
N.E.Kalogerakis
K.R.Islam *

* Corresponding author

Abstract

Urban environments worldwide face toxic heavy metal pollution originating from industrial discharge, municipal waste disposal, vehicular emissions, and atmospheric deposition. Kazakhstan, experiencing accelerated economic growth and extensive mining activities, contends with widespread heavy metal contamination in its soil-plant-air-water ecosystems. This study explores the potential of hyperaccumulating plants for phytoremediation in urban soils of Kazakhstan contaminated with Pb, Cd, and Co. Twelve plant species, including Korean Mint (*Lamiaceae*), Ornamental Cabbage (*Brassica oleracea*), Ageratum (*Ageratum houstonianum*), Coneflower (*Echinacea purpurea*), Amaranth (*Amaranthus Perfect* and *Amaranthus Emerald*), Fescue (*Festuca glauca*), Burning Bush (*Kochia scoparia*), Marigold (*Tagetes patula nana*), White Cabbage (*Brassica-Cavolo cappuccino BIANKO*), Tepary Bean (*Phaseolus acutifolius*), and Rapeseed (*Brassica napus*), were evaluated for growth and biomass production in urban soils spiked with two maximum permissible addition (MPA) treatments of Pb, Co, and Cd. The selected plants demonstrated varied responses to heavy metal stress, with Marigold (8.4 g shoot biomass/plant), Korean mint (10.5 g shoot biomass/plant), Rapeseed (19.9 g/shoot biomass), and Tepary bean (25.9 g shoot biomass/plant) exhibiting resilience or tolerance to Pb, Co, and Cd stresses. The results highlight the significant potential of these plants for efficient phytoremediation, showcasing their unique abilities to absorb and accumulate specific metals. Marigold, particularly, displayed noteworthy Pb accumulation (40.3 mg/kg biomass), resulting in reduced residual Pb concentrations in the soil (74.7 mg/kg). Conversely, White cabbage and Amaranth showed limited efficiency in Cd extraction, while Rapeseed and Tepary bean emerged as promising candidates for Cd phytoremediation. This study emphasizes the critical role of tailored plant species selection in designing effective phytoremediation strategies for specific metal-contaminated urban sites. A comprehensive understanding of the dynamics of metal accumulation and residual concentrations is crucial for the development of sustainable and efficient environmental remediation approaches. Further research is warranted to explore the long-term effects of different plant species on soil metal concentrations, refining and optimizing phytoremediation methods for urban soils grappling with toxic heavy metal contamination.

Keywords: Pot culture, lead, cadmium, cobalt, hyperaccumulators, shoot biomass.

Introduction

Urban soils are susceptible to heavy metals pollution from both point and non-point sources, including industrial discharge and emissions, chemical plants and spillage of petrochemicals, utilities and energy

: https://doi.org/10.18393/ejss.1522127
: https://ejss.fesss.org/10.18393/ejss.1522127
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

production, burning of fossil fuels, disposal of metal wastes, municipal waste disposal, and atmospheric deposition in response to human activities globally (Wei and Yang, 2010; Kakimov et al., 2013; Tefera et al., 2018; Yelikbayev et al., 2020; Silva et al., 2021; Toishimanov et al., 2023). The movement of traffic vehicles also emits heavy metals through various sources such as exhaust gases, incomplete fuel combustion, fuel additives, oil leaks, lining rupture, tire wear, and car washing (Amato et al., 2014; Werkenthin et al., 2014). Additionally, suspended particles from atmospheric emissions contribute to soil contamination and can be re-suspended as fugitive dust into the atmosphere (Woszczyk et al., 2018).

Heavy metals commonly found in urban contaminated soil-plant-air-water ecosystems include lead (Pb), chromium (Cr), arsenic (As), zinc (Zn), cadmium (Cd), copper (Cu), mercury (Hg), and nickel (Ni) in high concentrations (Minkina et al., 2014; Doabi et al., 2018; Woszczyk et al., 2018; Ramazanova et al., 2021; Silva et al., 2021). While Pb makes up about 14.8 mg/kg of the earth's crust (Wedepohl, 1995), it enters urban soil from vehicle exhaust gases and with dust and gases from various industrial facilities (Amato et al., 2014; Werkenthin et al., 2014). In soils, Pb accumulates for a long time, because it is not biodegradable. As it accumulates in soil-plant ecosystems, it becomes toxic to soil biology and public health (Zaborowska et al., 2016; Khanam et al., 2020). Likewise, Co is about 24 mg/kg of the earth's crust (Wedepohl, 1995), but it released into urban soils mainly from industrial sites when fossil fuels are burned (Li, 2001). In contrast, Cd makes up about 100 μg/kg of the earth's crust (Wedepohl, 1995), it sourced from the mining and metallurgical industries, fertilizers, and sewage sludge (Zaborowska et al., 2016).

Soils are the major sink for heavy metals especially Pb, Cd, and Co due to their persistence against biological or chemical degradation which can lead to an increased uptake by plants and their accumulation in living organisms (Gebrekidan et al., 2013; Doabi et al., 2018; Amoakwah et al., 2022). However, these metals do not have any biological function in public health or plant nutrition and are thus considered nonessential elements. Soil contamination with these toxic heavy metals, even at low concentrations, can disrupt the activity and biodiversity of ecological systems and cause a wide range of public health disorders, including cancers (Li et al., 2018; Ramazanova et al., 2021).

Due to the accelerated economic growth and indiscriminate mining activities, soil-plant-air-water ecosystems contaminated with heavy metals is common in Kazakhstan (Diacono et al., 2008; Kaliaskarova et al., 2019; Baubekova et al., 2021; Toishimanov et al., 2023; Zhyrgalova et al., 2024). Several research studies have suggested widespread contamination of urban soils in Kazakhstan with persistent heavy metals such as Pb, Cu, Va, Zn, Cd, and Co (Iztileu et al., 2016; Aiman et al., 2018; Muzychenko et al., 2017; Baubekova et al., 2021; Naimanova et al., 2024). These contaminants pose significant environmental risks and human hazards through direct ingestion or contact with contaminated ecosystems and the food chain, necessitating urgent remediation efforts (Baubekova et al., 2021; Ramazanova et al., 2021).

While chemical and physical methods are widely used for remediating and/or neutralizing heavy metal-contaminated soils, they often entail significant environmental trade-offs. Techniques such as soil excavation, chemical leaching, and thermal desorption are expensive and labor intensive, and can substantially disrupt the ecological balance of the treated site, resulting in potential drawbacks (Naimanova et al., 2024). Given the crucial need to address the growing heavy metals pollution concerns, research efforts must concentrate on proactive remediation of toxic heavy metals pollution-laden urban soils using environmentally compatible approaches. One such approach is phytoremediation, which involves using suitable plants that are highly adaptive and capable of growing in soils contaminated with heavy metals (Cho-Ruk et al., 2006; Yelikbayev et al., 2020; Toishimanov et al., 2023). These plants produce biomass with extensive root systems that actively absorb heavy metals from the soil and translocate them from root to shoot. This process allows the plants to bind and accumulate large amounts of heavy metals in their shoots without any visible phytotoxic effects, thereby acting as hyperaccumulators to remediate and rehabilitate contaminated sites (Marques et al., 2009; van der Ent et al., 2013; Yan et al., 2020).

It is reported that more than 500 plant species in 101 families, including members of *Asteraceae, Brassicaceae, Caryophyllaceae, Cyperaceae, Cunouniaceae, Fabaceae, Flacourtiaceae, Lamiaceae, Poaceae, Violaceae*, and *Euphobiaceae*, are capable of accumulating various metals (Krämer, 2010; van der Ent et al., 2013). Accumulation of metals occurs in approximately 0.2% of all angiosperms, especially in Brassicaceae (Krämer, 2010; Marques et al., 2009; Yan et al., 2020). Previous studies have indicated that though the heavy metals like, Cd, Pb and Ni are non-essential for plant growth, they are readily taken up and accumulated by certain plants (Cho-Ruk et al., 2006). These plants can accumulate Cd, As and some other traces of metals at-least 0.01%, Co, Cu, Cr, Ni and Pb 0.1%, and Mn and Ni 1% in dry-weight of shoot biomass (Reeves and Baker, 2000).

The maximum permissible addition (MPA) of the heavy metal / metalloid content in the soil is the key criteria to standardize the soil contamination (Vodyanitskii, 2016). While the MPAs of Cd, Co, and Pb are 0.76, 34, and 55 mg/kg, respectively, the concentration of heavy metals in urban soils of Kazakhstan, in some instances, exceeded their limits. Therefore, Pb, Cd, and Co pollution of urban soils poses a great potential threat to the environment and human health in Kazakhstan. Our hypothesis was that plants with inherent tolerance and capability for increased uptake and accumulation of toxic heavy metals would provide a proactive approach to phytoextraction in contaminated urban soils. The objective of our research was to evaluate the growth and shoot biomass production of diverse plants and their performance in phytoextraction of Pb, Cd, and Co from spiked contaminated urban soils.

Material and Methods

Soil properties

The pot culture experiment was conducted at the greenhouse in the Dept. of Chemical Processes and Industrial Ecology at Satbayev University, Almaty, Kazakhstan during 2021-2022. Composite soils in metropolitan Almaty were collected at 0-30 cm depth. Initial analyses have shown that soil had total organic carbon (SOC) 17. 6 g/kg, total phosphorus 4.7 g/kg, calcium carbonate 1.21 ±%, pH 8.1, cation exchange capacity 31.6 1 cmol$_+$/kg, total silica 143, aluminum 53, magnesium 4.7, potassium 26.5, iron 5.4, and titanium 5.4 g/kg, respectively. Total cobalt (Co), lead (Pb), and cadmium (Cd) concentrations were 13, 27, and 4.1 mg/kg, respectively.

Table 1. Heavy metals type, dose (MPA, maximum permissible addition), and name of the plants used in the experiment.

Heavy metal	Soil + 2 MPA = Total (mg/kg soil) conc.	Latin or botanical name	Common name
Cobalt	13+48 = 61	*Lamiaceae*	Korean Mint
	13+48 = 61	*Brassica oleracea*	Cabbage ornamental
	13+48 = 61	*Ageratum houstonianum*	Ageratum
	13+48 = 61	*Echinacea purpurea*	Coneflower
Lead	27+110 = 137	*Amaranthus*	Amaranth Perfect
	27+110 = 137	*Festuca glauca*	Fescue
	27+110 = 137	*Kochia scoparia*	Burning bush
	27+110 = 137	*Tagetes patula nana*	Marigold
Cadmium	4.1+1.5 = 5.6	*Amaranthus*	Amaranth Emerald
	4.1+1.5 = 5.6	*Brassica-Cavolo cappuccino BIANKO*	White cabbage
	4.1+1.5 = 5.6	*Phaseolus acutifolius*	Tepary bean
	4.1+1.5 = 5.6	*Brassica napus*	Rapeseed

Experimental design and cultural practices

A completely randomized design was followed to conduct the study with 12 different locally grown plant species (Figure 1), three different heavy metals (such as Co, Pb, and Cd), and replicated six times (Table 1). Prior to initiate the experiment, about 400 g of perlite was placed in plastic pots (height 19 cm x diameter 20.5 cm, with a surface area of 330 cm^2) followed by filling with 5 kg of air-dried soil on the top of perlite layer. Required volume of distilled water was added to the pot from the top and then allowed to equilibrate the soil moisture content.

For our experiment, Pb, Cd, and Co solutions were added based on a concentration of two MPA, which was calculated based on the following equation (Vodyanitskii, 2016):

$$\text{MPA (mg/kg)} = \text{NOEC} : 10$$

where the NOEC stands for no observed effect concentration, i.e., the maximal concentration exerting no significant influence on the growth and reproduction of the test organisms, and 10 is a coefficient.

Pb, Cd, and Co solutions were prepared with concentrations of 2 MPA, equivalent to 110, 1.5, and 48 mg/kg, respectively. Exactly 21.98, 0.596, and 29.63 g of $Pb(NO_3)_2$, $CdSO_4.8H_2O$, and $Co(NO_3)_2.6H_2O$ salts were dissolved in 800-mL of distilled water followed by addition of 10-mL of conc. HNO_3 and volume to 1-L solution for the respective 2 MPA solution of Pb, Cd, and Co. The 2 MPA solutions of Pb, Cd, and Co were added to the soil to bring the total concentration of Pb, Cd, and Co at 137, 5.6, and 61 mg/kg, respectively (Table 1).

After 3 days, 50 ml of distilled water was added to the surface of each pot, and then poured back the drainage into each pot in four repeated cycles for unform contamination of soils. The spiked contaminated soil was allowed to equilibrate for 33 days in order for Pb, Co, and Cd to react and bind to the soil. Once the experimental soils were equilibrated with the Pb, Co, and Cd, randomly selected six seeds of each plant were sown in potted soil as per treatments. Immediately after germination, the plant seedlings were watered daily as required, based on evapotranspiration. A basal dose of NPK fertilizers was applied to maintain uniform soil fertility for all experimental plants.

Figure 1. Experimental set-up with growing plants under greenhouse condition.

Analysis of soil chemical and physical properties

Composite field-moist soils collected prior to initiate the experiment were air-dried under shade at room temperature (25 ^{0}C) for a period of 15 days, ground with agate mortar and pestle, and 2-mm sieved. Soil pH was determined soil: distilled water suspension (1:5) following the standard glass electrode method (GOST 26423-85). Total soil organic carbon was analyzed, based on wet oxidation of soil with potassium dichromate and concentrated sulfuric acid following Tyurin colorimetric method (Jankauskas et al., 2006). Determination of carbonate in soils was performed by volumetric calcimeter method. The Kappen method was used to determine cation exchange capacity of soil (GOST 27821-88). Total silica, aluminum, magnesium, potassium, iron, and titanium was determined using an X-ray fluorescence energy-dispersive spectrometer PANalytical Epsilon-3. Soil particle size analysis (sand, silt and clay contents) was performed by pipette method (GOST 12536-2014).

Plant heavy metals analysis

After 90 days of plant growth, the shoot biomass was harvested at the base, weighted, and oven-dried at 55$\underline{+}$2^0 C for a period of 24 hr. until a constant was obtained. A portion of the oven-dried shoot biomass was ground with a Wiley Mill® grinder, sieved with a 125 µm mesh prior to digest, and analyze Cd, Co, and Pb using the standard EPA-3052 method (https://www.epa.gov/sites/default/files/2015-12/documents/3052.pdf).

Briefly, a 0.2 g processed sample was mixed with 3: 1: 1 mL ratio of HCl, HNO_3, and HF in standard Teflon tubes (vessels) for microwave digestion using the Speedwave Xpert DAP-60+ program (Table 2). After digestion, the digestates were allowed to cool and then diluted with distilled deionized water. The diluted samples were filtered using Whatman® filter paper to obtain clear aliquots. These aliquots were then analyzed for Cd, Co, and Pb using the Integrated Coupled Plasma Optical Emission Spectrophotometer Optima 8300, manufactured by Perkin Elmer Inc., USA.

Table 2. Program: Speedwave Xpert – DAP-60 +

Step	1	2	3
Time (^{0}C)	170	190	240
Pressure (bar)	50	50	50
Power (%)	80	90	100
Ta (min.)	2	2	2
Time (min)	10	20	30

Soil heavy metals analysis

After plant biomass harvest, soil samples collected from each replicated pot were air-dried under shade at room temperature (~ 25 ^{0}C) for a period of 15 days, ground with a agate mortar and pestle, and 250 µm sieved prior to analyze. Soils collected prior to establishing the experiment were also processed and analyzed for Pb, Co, and Cd concentrations in a similar manner, following the standard EPA-3052 method for heavy metals analysis (https://www.epa.gov/sites/default/files/2015-12/documents/3052.pdf).

Briefly, a 0.2 g sample of processed soil was mixed with 3: 1: 1 mL ratio of HCl, HNO_3, and HF in standard Teflon tubes (vessels) for microwave digestion at high power using the Speedwave Xpert DAP-60+ program (Table 2). After digestion, the Teflon tubes were allowed to cool at room temperature, and the digestates were diluted with distilled deionized water, filtered with Whatman filter paper, and analyzed for Cd, Co, and Pb concentration by the Perkin Elmer Optima 8300 Integrated Coupled Plasma-Optical Emission Spectrometry.

Quality analysis / quality control

After every 10 samples, a QC/QA sample prepared from certified standard solutions of Cd, Co, and Pb were determined to verify the analytical stability and quality with a relative standard deviation of QA/QC (5 to 10%). The detection limits of heavy metals such as Cd, Co, and Pb were 0.2, 0.2, and 0.3 µg/L, respectively. Analytical precision as determined by QA/QC procedures, reagent blanks, and internal standards, was better than ±10%.

Statistical analysis

One-way analysis of variance (ANOVA) was performed to evaluate the effects of selected plants (independent variable) on phytoremediation of heavy metals (dependent variable). Three separate ANOVAs were used for Cd, Co, and Pb, respectively. The plants used as an independent variable were considered as a fixed effect. Prior to the analysis, the normality of the data distribution was checked. Significant effects of the independent variable associated with Pb, Co, and Cd on plant shoot biomass production, Pb, Co, and Cd uptake in shoot biomass, and residual Pb, Co, and Cd concentrations in soil were separated by the Least Significant Difference (LSD) Test (Table 3). The software SAS 9.4 was employed for all statistical analyses, while graphs were created using SigmaPlot.

Table 3. Heavy metals effect on shoot biomass production and their residual distribution in soil and shoot uptake by plants (Mean data were presented with F values and one-way analysis of variance).

Heavy metal	Plants used (common name)	Shoot biomass (g/plant)	Residual metal (mg/kg soil)	Metal uptake (mg/kg plant)
Cobalt	Korean Mint	10.6	21.3	25.8
	Ageratum	7.0	40.0	13.7
	Cabbage ornamental	5.6	32.7	18.4
	Coneflower	1.8	27.0	22.1
	F-value	194.1	71.6	45.8
	Probability > F	0.001	<0.0001	<0.0001
Lead	Marigold	8.5	58.7	27.5
	Amaranth Perfect	2.0	95.0	26.0
	Burning bush	1.4	86.0	28.4
	Fescue	1.2	92.0	29.9
	F-value	445.2	3.0	6.0
	Probability > F	0.015	0.049	0.047
Cadmium	Tepary bean	26.1	5.1	0.56
	White cabbage	20.1	5.6	0.20
	Amaranth Emerald	0.77	5.4	0.32
	Rapeseed	0.25	5.0	0.63
	F-value	461.1	1.7	1.22
	Probability > F	0.002	0.043	0.036

Results and Discussion

Plant shoot biomass production

The application of 2 MPA Pb, Co, and Cd treatments significantly influenced the growth and shoot biomass production of tested plants used for phytoremediation (Table 3; Figure 2-4). Marigold demonstrated the highest shoot biomass production (8.4 g/plant) among Pb-treated plants, while Fescue (1.2 g/plant), Burning bush (1.4 g/plant), and Amaranth (1.9 g/plant) exhibited lower shoot biomass production, indicating their increased susceptibility to Pb toxicity (Table 3; Figure 2). These findings align with studies suggesting that Amaranth, Burning bush, and Fescue are adversely affected by Pb, experiencing decreased shoot biomass due to heightened Pb toxicity susceptibility linked to water and nutritional relations, leading to oxidative damage (Navabpour et al., 2020). Pb-induced structural changes, reduction in chlorophyll pigments, and altered carbon metabolism contribute to the observed negative impact on these plants (Rahman et al., 2013; Zulfiqar et al., 2019).

Similarly, Co exerted notable negative effects on the shoot biomass production of Coneflower (1.8 g/plant), Green cabbage (5.6 g/plant), and Ageratum (6.9 g/plant), whereas Korean mint displayed higher shoot biomass production (10.5 g/plant) (Table 3; Figure 3). The reduced biomass in coneflower, green cabbage, and ageratum under Co stress is consistent with previous research indicating that elevated Co concentrations generate reactive oxygen species (ROS), inhibit root growth, and disrupt nutrient uptake by plants (Valko et al., 2005; Mahey et al., 2020). Co-induced ROS disrupts photosystem II, the electron transport chain, and reduces pigments and nitrogen metabolism, contributing to the observed decline in biomass (Tewari et al., 2002; Ali et al., 2010).

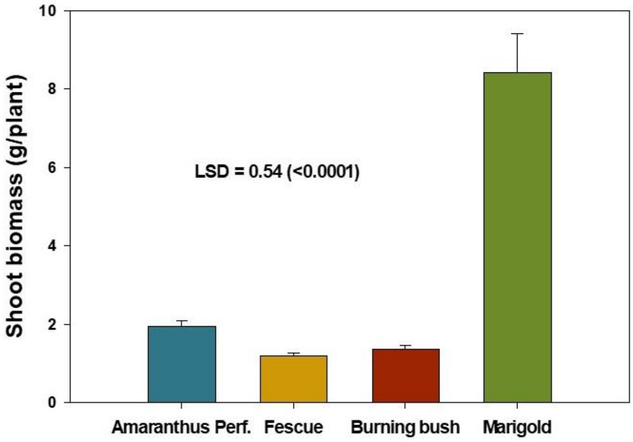


Figure 2. Effects of two maximum permissible addition (2 MPA) of lead on shoot biomass production of Amaranthus, Fescue, Burning bush, and Marigold (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

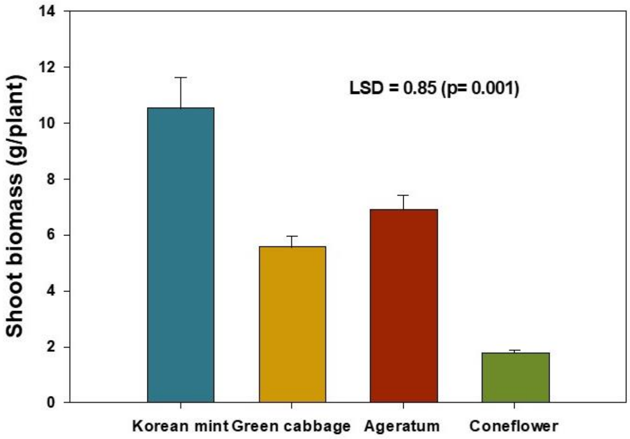


Figure 3. Effects of two maximum permissible addition (2 MPA) of cobalt on shoot biomass production of Korean mint, Green cabbage, Ageratum, and Coneflower (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

Furthermore, White cabbage (0.3 g/plant) and Amaranthus Emarald (0.8 g/plant) displayed significantly reduced shoot production due to the adverse effects of Cd, contrasting with the higher shoot biomass production in Rapeseed (19.9 g/plant) and Tepary bean (25.9 g/plant) (Table 3; Figure 4). The decreased shoot biomass in White cabbage and Amaranthus Emarald under Cd stress aligns with studies highlighting that Cd damages cells via ROS generation, inhibiting antioxidant enzymes and disrupting proteins (Valko et al., 2005; Bielen et al., 2013). Cd toxicity hampers nutrient uptake, induces oxidative damage, and disrupts plant metabolism, contributing to the observed reduction in shoot biomass (Gallego et al., 2012; Haider et al., 2021).

Our results suggest that Marigold, Korean mint, Rapeseed, and Tepary bean exhibit resilience or tolerance to Pb, Co, and Cd stresses, making them potential candidates for phytoremediation efforts in contaminated environments. The distinct responses observed among the tested plants underscore the importance of selecting suitable species for specific metal-contaminated sites, emphasizing their unique capacities to mitigate the adverse effects of Pb, Co, and Cd toxicity.

Plant uptake of heavy metals

The investigation into shoot biomass concentrations of Pb, Co, and Cd across diverse plant species provides crucial insights into their metal accumulation capabilities and potential roles in phytoremediation (Table 3). Marigold emerged as an outstanding accumulator of Pb, exhibiting a remarkable shoot biomass concentration of 40.3 mg/kg, surpassing Fescue and Burning bush (Table 3; Figure 5). The substantial difference is highlighted by Marigold's Pb accumulation being 1.3, 1.4, and 1.6 times higher than Fescue, Burning bush, and Amaranth, respectively. Additionally, Marigold demonstrated a noteworthy 29.6% absorption of Pb from the soil, showcasing its efficiency in lead uptake and accumulation. In contrast, Fescue, Burning bush, and Amaranth displayed lower Pb absorption percentages (22%, 20.9%, and 19.1%, respectively), suggesting their comparatively lower metal-accumulating potential.

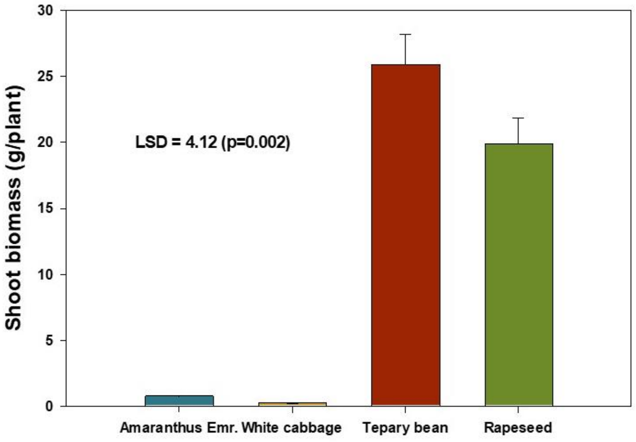


Figure 4. Effects of two maximum permissible addition (2 MPA) of cadmium on shoot biomass production of Amaranthus, White cabbage, Tepary bean, and Rapeseed (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

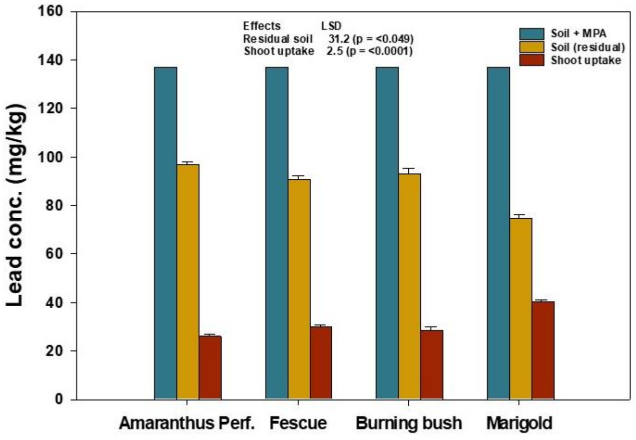


Figure 5. Lead concentration in Amaranthus, Fescue, Burning bush, and Marigold shoot biomass under two maximum permissible addition (2 MPA) of lead in the soil (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

Distinct responses to Co exposure were observed, with Korean mint exhibiting the highest shoot biomass concentration (25.8 mg/kg), followed by Coneflower and Green cabbage (Table 3; Figure 6). In contrast, Ageratum displayed the lowest Co concentration (13.7 mg/kg). The varying Co levels highlight the diverse abilities of these plants in Co uptake and accumulation. Korean mint, Coneflower, Green cabbage, and Ageratum absorbed 42.3%, 36.2%, 30.2%, and 22.4% of Co from the soil, respectively, showcasing their potential roles in Co phytoremediation.

Conversely, Cd concentrations in the shoot biomass remained relatively low, ranging from 0.20 to 0.63 mg/kg (Table 3; Figure 7). Rapeseed exhibited the highest Cd concentration, while Amaranth and White cabbage displayed the lowest. The modest variations in Cd levels suggest a limited uptake of this metal. Rapeseed and Tepary bean, with absorption percentages of 11.2% and 10.1%, respectively, present as potential candidates for Cd phytoremediation.

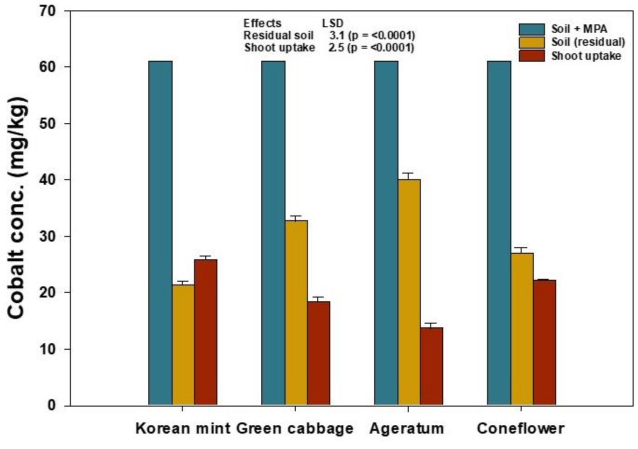


Figure 6. Cobalt concentration in Korean mint, Green cabbage, Ageratum, and Coneflower shoot biomass under two maximum permissible addition (2 MPA) of cobalt in the soil (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

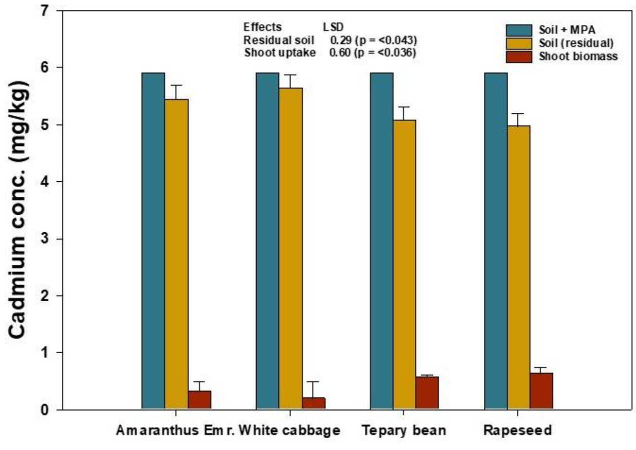


Figure 7. Cadmium concentration in Amaranthus, White cabbage, Tepary bean, and Rapeseed shoot biomass under two maximum permissible addition (2 MPA) of cadmium in the soil (Mean values were presented with standard error. Means separated by same lower-case letter in the bars were not significantly different at p≤0.05 among the plants).

The study aligns with existing literature emphasizing that increasing toxic metal levels in the soil lead to elevated uptake by plants, influencing their metal concentrations (Pb, Cu, Cd, and Zn), particularly in leaves

(Brown et al., 1995; Rahman et al., 2013). The observed differential responses among the tested plant species underscore the importance of selecting appropriate hyperaccumulators based on their metal concentrations. This information is crucial for developing effective and targeted phytoremediation strategies tailored to specific metal-contaminated environments. The ability of certain plants, such as Marigold, Korean mint, Rapeseed, and Tepary bean, to accumulate specific metals highlights their potential utility in environmental remediation efforts.

Residual heavy metals in soil

The investigation into residual metal concentrations in the soil provides valuable insights into the effectiveness of various plant species in mitigating Pb, Co, and Cd pollution (Table 3). The highest residual Pb concentrations in the soil were observed under Amaranth, Burning bush, and Fescue, measuring 96.7, 93, and 90.7 mg/kg, respectively. In contrast, Marigold exhibited the lowest residual Pb concentration of 74.7 mg/kg, relative to the total Pb concentration of 137 mg/kg in the contaminated soil (Table 3; Figure 5). These findings suggest that Amaranth, Burning bush, and Fescue may contribute to a prolonged presence of Pb in the soil due to their limited capacity for uptake and accumulation, while Marigold demonstrates potential for Pb phytoremediation by reducing residual concentrations.

Soils under Ageratum, Green cabbage, Coneflower, and Korean mint displayed the highest residual concentrations of Co compared to the total Co concentration (61 mg/kg) in the spiked contaminated soils (Tabel 3; Figure 6). This indicates that these plant species might have a limited capacity to extract and accumulate Co from the soil, leading to elevated residual Co concentrations. The persistence of Co in the soil under these plants underscores the need for careful consideration of plant selection in Co-contaminated environments.

Conversely, residual soil Cd concentrations were highest under White cabbage and Amaranth, while Rapeseed and Tepary beans exhibited the lowest concentrations, relative to the total Cd concentration in the spiked contaminated soils (Table 3; Figure 7). These results suggest that White cabbage and Amaranth may have a limited ability to extract Cd from the soil, contributing to higher residual concentrations in soil. In contrast, Rapeseed and Tepary beans demonstrate potential for Cd phytoremediation by reducing Cd concentrations in the soil.

The observed variations in residual metal concentrations in soil highlight the importance of plant species selection in phytoremediation strategies. While certain plants may effectively reduce metal concentrations in the soil, others may contribute to the prolonged presence of metals. Understanding the dynamics of residual metal concentrations is crucial for designing sustainable and efficient phytoremediation approaches tailored to specific metal-contaminated environments.

Conclusion

Marigold exhibits resilience to Pb toxicity, while Fescue, Burning bush, and Amaranth show heightened susceptibility. Similarly, Coneflower, Green cabbage, and Ageratum display reduced biomass under Co stress, contrasting with Korean mint. White cabbage and Amaranthus Emarald exhibit reduced shoot production under Cd stress, unlike Rapeseed and Tepary bean. Marigold, Korean mint, Rapeseed, and Tepary bean emerge as potential candidates for phytoremediation. The diverse responses underscore the importance of tailored species selection for specific metal-contaminated sites. Insights into metal accumulation capacities highlight the pivotal role of plant selection in effective environmental remediation strategies. Further research is needed to understand long-term effects of heavy metals concentrations in soil and to refine phytoremediation approaches.

Acknowledgement

This research was funded by the Scientific Committee of the Ministry of Education and Science of the Government of the Republic of Kazakhstan (Grant No. AP08957443).

References

Aiman, N., Gulnaz, S., Alena, M., 2018. The characteristics of pollution in the big industrial cities of Kazakhstan by the example of Almaty. *Journal of Environmental Health Science and Engineering* 16: 81–88.

Ali, B., Hayat, S., Hayat, Q., Ahmad, A., 2010. Cobalt stress affects nitrogen metabolism, photosynthesis and antioxidant system in chickpea (*Cicer arietinum* L.). *Journal of Plant Interactions* 5: 223–231.

Amato, F., Alastuey, A., de la Rosa, J., Gonzalez Castanedo, Y., Sánchez de la Campa, A.M., Pandolfi, M., Lozano, A., Contreras González, J., Querol, X., 2014. Trends of road dust emissions contributions on ambient air particulate levels at rural, urban and industrial sites in southern Spain. *Atmospheric Chemistry and Physics* 14: 3533–3544.

Amoakwah, E., Ahsan, S., Rahman, M. A., Asamoah, E., Essumang, D.K., Ali, M., K.R. Islam., 2020. Assessment of heavy metal pollution of soil-water-vegetative ecosystems associated with artisanal gold mining. *Soil and Sediment Contamination: An International Journal* 29: 788-803.

Baubekova, A., Akindykova, A., Mamirova, A., Dumat, C., Jurjanz, S., 2021. Evaluation of environmental contamination by toxic trace elements in Kazakhstan based on reviews of available scientific data. *Environmental Science and Pollution Research* 28: 43315-43328.

Bielen, A., Remans, T., Vangronsveld, J., Cuypers, A., 2013. The influence of metal stress on the availability and redox state of ascorbate, and possible interference with its cellular functions. I*nternational Journal of Molecular Sciences* 14: 6382-6413.

Brown, S.L., Chaney, R.L., Angle, J.S., Baker, A.J.M., 1995. Zinc and cadmium uptake by hyperaccumulator *Thlaspi caerulescens* grow in the nutrient solution. *Soil Science Society of America Journal* 59: 125-133.

Cho-Ruk, K., Kurukote, J., Supprung, P., Vetayasuporn, S., 2006. Perennial plants in the phytoremediation of lead-contaminated soils. *Biotechnology* 5: 1-4.

Diacono, E., Faye, B., Meldebekova, A., Konuspayeva, G., 2008. Plant, water and milk pollution in Kazakhstan. In: Impact of Pollution on Animal Products. Sinyavskiy, Y., Faye, B. (Eds.). Springer Netherlands, Dordrecht, pp. 107–116.

Doabi, S.A., Karami, M., Afyuni, M., Yeganeh, M., 2018. Pollution and health risk assessment of heavy metals in agricultural soil, atmospheric dust and major food crops in Kermanshah province, Iran. *Ecotoxicology and Environmental Safety* 163: 153–164.

Gallego, S.M., Pena, L.B., Barcia, R.A., Azpilicueta, C.E., Iannone, M.F., Rosales, E.P., Benavides, M.P., 2012. Unravelling cadmium toxicity and tolerance in plants: insight into regulatory mechanisms. *Environmental and Experimental Botany* 83: 33-46.

Gebrekidan, A., Weldegebriel, Y., Hadera, A., Van der Bruggen, B., 2013. Toxicological assessment of heavy metals accumulated in vegetables and fruits grown in Ginfel river near Sheba Tannery, Tigray, Northern Ethiopia. *Ecotoxicology and Environmental Safety* 95: 171-178.

GOST 12536-2014. Soils - Methods of laboratory granulometric (grain-size) and microaggregate distribution. Available at [Access date: 11.03.2024]: https://www.russiangost.com/p-138335-gost-12536-2014.aspx

GOST 27821-88. Soils. Determination of base absorption sum by Kappen method. Available at [Access date: 11.03.2024]: https://www.russiangost.com/p-49750-gost-27821-88.aspx?

GOST 26423-85. Soils - Methods for determination of specific electric conductivity, pH and solid residue of water extract. Available at [Access date: 11.03.2024]: https://www.russiangost.com/p-16105-gost-26423-85.aspx

Haider, F.U., Liqun, C., Coulter, J.A., Cheema, S.A., Wu, J., Zhang, R., Wenjun, M., Farooq, M., 2021. Cadmium toxicity in plants: Impacts and remediation strategies. *Ecotoxicology and Environmental Safety* 211: 111887.

Iztileu, A., Grebeneva, O., Otarbayeva, M., Zhanbasinova, N., Ivashina, E., Duisenbekov, B., 2016. Intensity of soil contamination in industrial centers of Kazakhstan. CBU International Conference Proceedings, ISE Research Institute 1: 374-380.

Jankauskas, B., Jankauskiene, G., Slepetiene, A., Fullen, M.A., Booth, C.A., 2006. International comparison of analytical methods of determining the soil organic matter content of Lithuanian Eutric Albeluvisols. *Communications in Soil Science and Plant Analysis* 37: 707-720.

Kakimov, A., Kakimova, Z., Yessimbekov, Z., Bepeyeva, A., Zharykbasova, K., Zharykbasov, Y., 2013. Heavy metals distribution in soil, water, vegetation and meat in the regions of East-Kazakhstan. *Journal of Environmental Protection* 4: 1292-1295.

Kaliaskarova, Z., Aliyeva, Z., Ikanova, A., Negim, E., 2019. Soil pollution with heavy metals on the land of the Karasai landfill of municipal solid waste in Almaty city. *News of the Academy of Science of the Republic of Kazakhstan, series Geology and Technical Science* 6: 256-267.

Khanam R, Kumar A, Nayak AK, Shahid M, Tripathi R, Vijayakumar S, Bhaduri, D., Kumar, U., Mohanty, S., Panneerselvam, P., Chatterjee, D., Satapathy, B.S., Pathak, H., 2020. Metal(loid)s (As, Hg, Se, Pb and Cd) in paddy soil: Bioavailability and potential risk to human health. *Science of the Total Environment* 699: 134330.

Krämer, U., 2010. Metal hyperaccumulation in plants. *Annual Review of Plant Biology* 61: 517-534.

Li, X.D., Poon, C.S., Liu, P.S., 2001. Heavy metal contamination of urban soils and street dusts in Hong Kong. *Applied Geochemistry* 16: 1361–1368.

Li, G., Sun, G.X., Ren, Y., Luo, X.S., Zhu, Y.G., 2018. Urban soil and human health: a review. *European Journal of Soil Science* 69: 196-215.

Mahey, S., Kumar, R., Sharma, M., Kumar, V., Bhardwaj, R., 2020. A critical review on toxicity of cobalt and its bioremediation strategies. *SN Applied Sciences* 2: 1279.

Marques, A.P.G.C, Rangel, A.O.S.S., Castro, P.M.L., 2009. Remediation of heavy metal contaminated soils: phytoremediation as a potentially promising clean-up technology. *Critical Reviews in Environmental Science and Technology* 39: 622-654.

Minkina, T., Mandzhieva, S., Motusova, G., Burachevskaya, M., Nazarenko, O., Sushkova, S., Kızılkaya, R., 2014. Heavy metal compounds in a soil of technogenic zone as indicate of its ecological state. *Eurasian Journal of Soil Science* 3(2): 144 – 151.

Muzychenko, I., Jamalova, G., Mussina, U., Kazulis, V., Blumberga, D., 2017. Case study of lead pollution in the roads of Almaty. *Energy Procedia* 113: 369–376.

Naimanova, A., Akhmetova, S., Issayeva, A., Vyrakhmanova, A., Alipbekova, A., 2024. Phytoaccumulation of heavy metals in South Kazakhstan soils (Almaty and Turkestan Regions): An evaluation of plant-based remediation potential. *International Journal of Design & Nature and Ecodynamics* 19: 451-464.

Navabpour, S., Yamchi, A., Bagherikia, S., Kafi, H., 2020. Lead-induced oxidative stress and role of antioxidant defense in wheat (*Triticum aestivum* L.). *Physiology and Molecular Biology of Plants* 26: 793-802.

Rahman, M.M., Azirun, S.M., Boyce, A.N., 2013. Enhanced accumulation of copper and lead in Amaranth (*Amaranthus paniculatus*), Indian Mustard (*Brassica juncea*) and Sunflower (*Helianthus annuus*) *PLOS ONE* 8: e62941.

Ramazanova, E., Lee, S.W., Lee, W., 2021. Stochastic risk assessment of urban soils contaminated by heavy metals in Kazakhstan. *Science of the Total Environment* 750: 141535.

Reeves, R.D., Baker, A.J.M., 2000. Metal- accumulating plants. In: Phytoremediation of toxic metals: using plants to clean-up the environment. Raskin, I., Ensley, B.D. (Eds.). John Wiley and Sons. New York, USA. pp. 193-230.

Silva, H.F., Silva, N.F., Oliveira, C.M., Matos, M.J., 2021. Heavy metals contamination of urban soils—A decade study in the city of Lisbon, Portugal. *Soil Systems* 5: 27.

Tefera, M., Gebreyohannes, F., Saraswathi, M., 2018. Heavy metal analysis in the soils of in and around Robe town, Bale zone, South Eastern, Ethiopia. *Eurasian Journal of Soil Science* 7(3): 251 - 256.

Tewari, R.K., Kumar, P., Sharma, P.N., Bisht, S.S. 2002. Modulation of oxidative stress responsive enzymes by excess cobalt. *Plant Science* 162: 381388.

Toishimanov, M., Abilda, Z., Daurov, D., Daurova, A., Zhapar, K., Sapakhova, Z., Kanat, R., Stamgaliyeva, Z., Zhambakin, K., Shamekova, M., 2023. Phytoremediation properties of sweet potato for soils contaminated by heavy metals in South Kazakhstan. *Applied Sciences* 13: 9589.

Valko, M., Morris, H., Cronin, M.T.D. 2005. Metals, toxicity and oxidative stress. *Current Medicinal Chemistry* 12: 1161-1208.

van der Ent, A., Baker, A.J.M., Reeves, R.D., Pollard, A.J., Schat, H., 2013. Hyperaccumulators of metal and metalloid trace elements: facts and fiction. *Plant and Soil* 362: 319-334.

Vodyanitskii, Y.N., 2016. Standards for the contents of heavy metals in soils of some states. *Annals of Agrarian Science* 14: 257-263.

Wedepohl, K.H., 1995. The composition of the continental crust. *Geochimica et Cosmochimica Acta* 59: 1217–1232.

Wei, B., Yang, L., 2010. A review of heavy metal contaminations in urban soils, urban road dusts and agricultural soils from China. *Microchemical Journal* 94: 99-107.

Werkenthin, M., Kluge, B., Wessolek, G., 2014. Metals in European roadside soils and soil solution-A review. *Environmental Pollution* 189: 98-110.

Yan, A., Wang, Y., Tan, S.N., Yusof, M.L.M., Ghosh, S., Chen, Z., 2020. Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. *Frontiers in Plant Science* 11: 359.

Yelikbayev, B.K., Pagano, M.C., Jamalova, G.A., 2020. Hyperaccumulator plants for phytoremediation of soil contaminated with heavy metals. *Bulletin of National Academy of Sciences of the Republic of Kazakhstan* 387: 34-40.

Zaborowska, M., Kucharski, J., Wyszkowska, J., 2016. Biological activity of soil contaminated with cobalt, tin, and molybdenum. *Environmental Monitoring and Assessment* 188: 398.

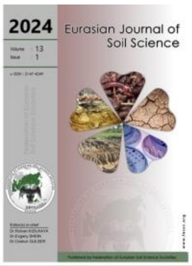
Zhyrgalova, A., Yelemessov, S., Ablaikhan, B., Aitkhozhayeva, G., Zhildikbayeva, A., 2024. Assessment of potential ecological risk of heavy metal contamination of agricultural soils in Kazakhstan. *Brazilian Journal of Biology* 84: e280583.

Zulfiqar, U., Farooq, M., Hussain, S., Maqsood, M., Hussain, M., Ishfaq, M., Ahmad, M., Anjum, M.Z., 2019. Lead toxicity in plants: Impacts and remediation. *Journal of Environmental Management* 250: 109557.

Eurasian Journal of Soil Science 2024, 13(4), 358 - 365

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org


2024 Eurasian Journal of Soil Science

Impact of petroleum contamination on soil properties in Absheron Peninsula, Azerbaijan

Alovset Guliyev [a,*], Rahila Islamzade [a], Parvana Suleymanova [b], Tunzala Babayeva [b], Azade Aliyeva [b], Xayala Haciyeva [b]

[a] Institute of Soil Science and Agrochemistry, Baku, Azerbaijan
[b] Sumgayit State University, Sumgayit, Azerbaijan

Article Info
Received : 05.12.2023
Accepted : 08.08.2024
Available online: 12.08.2024

Author(s)
A.Guliyev *
R.Islamzade
P.Suleymanova
T.Babayeva
A.Aliyeva
X.Haciyeva

* Corresponding author

Abstract

This study aims to assess the extent of hydrocarbon and heavy metal contamination in soils from specific areas on Azerbaijan's Absheron Peninsula, including Absheron, Suraxanı, and Baku, and to evaluate the impact of this contamination on soil properties. Soil samples were analyzed for Total Petroleum Hydrocarbons (TPH) and heavy metals, including aluminum, arsenic, cadmium, lead, and iron, alongside assessments of soil physical, chemical and biological properties. The results revealed significant contamination across all studied areas, particularly in Suraxanı, where TPH levels reached 190 ± 20 mg/kg, exceeding the environmental standard of 100 mg/kg. Similarly, Suraxanı soils exhibited alarmingly high concentrations of heavy metals, with aluminum at 30,128 ± 1,500 mg/kg, arsenic at 50.94 ± 2.5 mg/kg, and cadmium at 0.153 ± 0.01 mg/kg, all surpassing acceptable limits. These contaminants severely degraded soil health, evidenced by increased bulk density (1.7 g/cm^3 in Suraxanı) and reduced soil porosity. Microbial activity, a key indicator of soil fertility, was also markedly lower in contaminated regions, with the total bacterial count in Suraxanı being less than half that of the uncontaminated area. The findings underscore the urgent need for comprehensive soil management practices and stricter environmental regulations to mitigate contamination's adverse effects and protect both ecosystems and public health in Azerbaijan's petroleum contaminated areas.

Keywords: Soil contamination, hydrocarbons, heavy metals, soil properties, Azerbaijan.

Introduction

Environmental pollution has become a significant global issue, driven by rapid industrial development and energy production activities. Among the various forms of pollution, soil contamination is particularly concerning due to its lasting impact on ecosystems. Soil pollution primarily occurs through the introduction of pollutants such as petroleum hydrocarbons and heavy metals, leading to severe adverse effects on vegetation, water quality, and overall biodiversity (Sushkova et al., 2020; Rajput et al., 2022; Dudnikova et al., 2023). The degradation of the physical, chemical, and biological properties of contaminated soils poses a threat not only to natural ecosystems but also to human health (Minnikova et al., 2022).

The environmental challenges in Azerbaijan can be traced to several key historical and political factors (Sanal, 2001). These include: i) the environmental insensitivity during the Soviet era, where environmental resources were perceived as free goods, combined with outdated production technologies and the uncontrolled release of industrial waste into nature; ii) the environmental destruction and pollution resulting from the conflict initiated by neighboring Armenia over the Nagorno-Karabakh region, following the collapse of the Soviet Union; and iii) the post-independence period marked by political instability, uncertainty in transitioning from

: https://doi.org/10.18393/ejss.1531959
: https://ejss.fesss.org/10.18393/ejss.1531959
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

a socialist to a capitalist system, and weaknesses in governance, which led to the neglect of environmental issues (Ünal, 2000). In this context, Azerbaijan faces significant environmental challenges, including: i) issues related to the Caspian Sea, which is significantly affected by the discharge of approximately 3 million cubic meters of wastewater containing various chemical substances and around 100,000 tons of oil product waste annually, particularly near populated areas such as Baku; ii) the unregulated disposal of waste generated from the processing of petroleum, gas, and other mineral resources; and iii) the decline in the quality and productivity of arable lands due to intensive use and improper agricultural practices, which has led to increased reliance on chemical fertilizers and pesticides, thereby exacerbating soil and water contamination (Zengin and Öztaş, 2007; Babayeva et al., 2024).

Azerbaijan, located at the crossroads of Eastern Europe and Western Asia, has a long history of oil production dating back to the late 19th century. The country is one of the world's oldest oil producers and has made significant contributions to the global oil supply (Rasizade, 1999). The Absheron Peninsula has been the focal point of Azerbaijan's oil industry. Intensive oil extraction and refining activities in this region have led to extensive soil contamination by hydrocarbons and heavy metals. These pollutants have altered the physical, chemical, and biological properties of soils in regions such as Baku, Absheron, and Suraxanı within the Absheron Peninsula, negatively impacting soil fertility and ecosystem health (Malling, 2014; The World Factbook, 2024).

In this study, soil samples from the Absheron, Suraxanı, and Baku regions of the Absheron Peninsula were analyzed and compared with samples from an uncontaminated area. The focus of this research is to evaluate how these soils have been affected by pollutants such as Total Petroleum Hydrocarbons (TPH) and heavy metals, and to assess the impact of these pollutants on the physical, chemical, and biological properties of the soils.

Material and Methods

Study area and climatic conditions

This study was conducted in three heavily industrialized regions of the Absheron Peninsula, Azerbaijan—Absheron, Suraxanı, and Baku-along with an uncontaminated control area for comparative analysis. The Absheron Peninsula, which includes Baku, is a significant geographical feature of Azerbaijan, extending 60 km eastward into the Caspian Sea with a maximum width of 30 km. The region is characterized by a mildly hilly landscape, dissected by ravines and dotted with salt lakes, particularly in the areas leading to the Absheron National Park.

Geologically, the Absheron Peninsula features deposits from various geological periods, including the Cretaceous, Palaeogene, Neogene, Pliocene, and Quaternary. The lithology is predominantly composed of clays, sandy clays, sands, and limestones, with thick sandy clay sediments particularly in areas with highly mineralized groundwater. These geological characteristics significantly influence the local environment, contributing to the unique challenges of managing soil and water resources in the region (Israfilov, 2006).

Climatically, the Absheron Peninsula has a temperate semi-arid climate (Köppen climate classification: BSk), making it the driest part of Azerbaijan. The region experiences hot, dry summers and cool, occasionally wet winters, with strong winds present throughout the year. The average annual temperature in the region is approximately 14.4°C, with January being the coldest month at 3.0°C and July the hottest at 25.7°C. Annual precipitation is sparse, typically around or less than 200 mm, with the majority falling outside the summer months. The natural vegetation consists of dry steppe and semi-desert, which, coupled with the arid climate, necessitates irrigation for local agriculture.

Environmental concerns on the Absheron Peninsula are significant due to the extensive petrochemical and refining industries. These activities have severely impacted the local environment, particularly the Caspian Sea shore and surrounding areas. As a result, the Absheron Peninsula, including Baku and Suraxanı, is considered one of the most ecologically degraded regions in the world (Malling, 2014; The World Factbook, 2024).

For the purposes of this study, soil samples were collected from the Absheron, Suraxanı, and Baku regions and were compared with samples from an uncontaminated control area. This approach was used to assess the extent of soil contamination by petroleum hydrocarbons and heavy metals, as well as to evaluate the physical, chemical, and biological properties of the soils in these heavily industrialized regions.

Soil sampling and analysis

Soil samples were collected from areas contaminated with crude oil in the Absheron, Suraxanı, and Baku regions of the Absheron Peninsula, Azerbaijan (Figure 1). These samples were obtained in May 2018 from five randomly selected sites within each region and then combined to create composite samples. The soil was sampled from a depth of 0-20 cm. Additionally, uncontaminated soil samples were collected from Suraxanı Park, a site specifically established using clean soil imported from other regions of Azerbaijan.

The collected soil samples were divided into two portions. The first portion was immediately stored at +4°C to preserve the biological properties of the soil for subsequent analysis. The second portion was air-dried in the shade, crushed gently with a wooden mallet, and sieved through a 2 mm mesh to prepare it for the determination of Total Petroleum Hydrocarbons (TPH), heavy metals, and other soil physical and chemical properties.

Figure 1. Locations of Soil Sampling Sites on the Absheron Peninsula

Total petroleum hydrocarbon analysis

The Total Petroleum Hydrocarbons (TPH) in the soil samples were determined using EPA Method 9071B for n-Hexane Extractable Material (HEM) in sludge, sediment, and solid samples (EPA, 1998). Soil samples were chemically dried with anhydrous sodium sulfate and then extracted using n-hexane in a Soxhlet apparatus. The extract was subsequently evaporated to dryness, and the remaining residue was weighed. The concentration of TPH was expressed in mg/kg.

Heavy metal analysis

Heavy metals, including aluminum, arsenic, cadmium, lead, iron, nickel, zinc, chromium, copper, and mercury, were analyzed using Inductively Coupled Plasma—Optical Emission Spectrometry (ICP-OES) as outlined in EPA Method 6010D (EPA, 2018). Soil samples were digested using a microwave digestion system with a mixture of concentrated nitric acid and hydrochloric acid to ensure complete breakdown of the sample matrix. The digested samples were then analyzed for metal concentrations using ICP-OES, and the results were expressed in mg/kg. Quality control procedures, including the use of standard reference materials, calibration standards, and blanks, were rigorously followed to ensure the accuracy and precision of the results.

Soil properties analysis

The physical properties of the collected soil samples were determined as follows: soil texture was analyzed using the hydrometer method (Bouyoucos, 1962); bulk density was measured using the core method (Blake and Hartge, 1986); porosity was determined with a pycnometer (Danielson and Sutherland, 1986); and water retention capacity was assessed using a pressure plate apparatus (Klute, 1986).

The chemical properties of the soil samples were also analyzed: pH was measured in a 1:1 soil-to-distilled water suspension using a pH meter (McLean, 1982); organic matter content was determined by the chromic acid titration method (Walkley and Black, 1934); total nitrogen was measured using the Kjeldahl method (Bremner, 1965); available phosphorus was extracted with 0.5M NaHCO3 and quantified using a spectrophotometer (Olsen and Dean, 1965); and available potassium was extracted with 1 N NH4OAc and measured using a flame photometer (Thomas, 1965).

The biological properties of the soil were evaluated by determining microbial activity, including total bacterial, fungal, and actinomycete counts. Microbial counts were performed using the plate count method (Wollum II, 1965), with results expressed as colony-forming units (CFU) per gram of dry soil.

Results and Discussion

Hydrocarbon levels in soils

The assessment of hydrocarbon levels in soils across different regions of Azerbaijan reveals significant contamination, highlighting the environmental impact of industrial activities. The concentration of total petroleum hydrocarbons (TPH) was measured in Absheron, Suraxanı, Baku, and an uncontaminated control area. The results are presented in Table 1.

Table 1. Concentration of total petroleum hydrocarbons (TPH) in different areas

Region	TPH Concentration (mg/kg)	Environmental Standard (mg/kg)
Absheron (Area A)	170 ± 15	100
Suraxanı (Area B)	190 ± 20	100
Baku (Area C)	160 ± 18	100
Uncontaminated Area	80 ± 10	100

The data indicates that all studied regions, except the uncontaminated area, exceed the environmental standard of 100 mg/kg for TPH. Suraxanı exhibits the highest levels of contamination, with an average TPH concentration of 190± 20 mg/kg, reflecting its extensive industrial activities. Baku and Absheron also show significantly high concentrations, with averages of 160 mg/kg and 170 mg/kg, respectively, indicative of their historical roles as major oil production centers. In contrast, the uncontaminated control area has a TPH level of only 80 mg/kg, underscoring the impact of industrial activities on soil health in the other regions. These elevated hydrocarbon levels underscore the urgent need for targeted soil remediation and pollution control measures. Strategies such as bioremediation and phytoremediation, coupled with stricter environmental regulations, are essential to mitigate the adverse effects on soil health, local ecosystems, and public health (Praveen and Nagalakshmi, 2022; Sánchez-Castro et al., 2023; Ashkanani et al., 2024). Robust intervention in highly contaminated areas like Suraxanı (Area B) is particularly critical to prevent further environmental degradation and health risks.

Heavy metal content in soils

The analysis of heavy metal content in soils across different regions of Azerbaijan reveals significant contamination, highlighting the environmental impact of industrial activities. The concentrations of various heavy metals were measured in Absheron, Suraxanı, Baku, and an uncontaminated control area. The results are presented in Table 2.

Table 2. Concentration of heavy metals in different areas

Heavy Metal	Absheron (Area A) (mg/kg)	Suraxanı (Area B) (mg/kg)	Baku (Area C) (mg/kg)	Uncontaminated Area (Area D) (mg/kg)	Environmental Standard (mg/kg)
Aluminum (Al)	2500 ± 200	30128 ± 1500	10000 ± 500	1733 ± 150	5000
Arsenic (As)	5.0 ± 0.4	50.94 ± 2.5	10.0 ± 0.8	0.76 ± 0.05	10
Cadmium (Cd)	0.05 ± 0.01	0.153 ± 0.01	0.1 ± 0.01	0.005 ± 0.001	0.05
Lead (Pb)	10.0 ± 1.0	15.07 ± 1.2	5.0 ± 0.5	1.48 ± 0.1	10
Iron (Fe)	3000 ± 250	17809 ± 1200	8000 ± 600	1992 ± 150	5000
Nickel (Ni)	7.0 ± 0.5	40.96 ± 2.1	12.0 ± 0.8	2.42 ± 0.2	10
Zinc (Zn)	10.0 ± 0.7	59.41 ± 4.0	20.0 ± 1.5	4.61 ± 0.3	30
Chromium (Cr)	14.62 ± 1.0	50.94 ± 3.0	20.0 ± 1.5	10.0 ± 0.8	25
Copper (Cu)	6.61 ± 0.5	29.31 ± 2.0	15.0 ± 1.2	10.0 ± 0.7	20
Mercury (Hg)	<0.06	0.156 ± 0.01	0.1 ± 0.01	<0.06	±

The data indicates that all studied regions, except the uncontaminated area, exhibit heavy metal concentrations that exceed the environmental standards. Suraxanı (Area B) exhibits the most extreme contamination levels, particularly with aluminum (30128 mg/kg), arsenic (50.94 mg/kg), and iron (17809 mg/kg). These values are far above the environmental standards, reflecting the severe impact of industrial activities in this region. Baku (Area C) and Absheron (Area A) also show significant contamination, with various metals such as aluminum, iron, and lead exceeding acceptable limits. In contrast, the uncontaminated control area shows much lower levels of heavy metals, confirming its status as a control site. These elevated levels of heavy metals underscore the urgent need for remediation efforts. Techniques such as soil washing, bioremediation, and phytoremediation, along with stricter industrial discharge regulations, are critical to mitigate the harmful effects of heavy metal contamination on soil health, local ecosystems, and public health (Praveen and Nagalakshmi, 2022; Sánchez-Castro et al., 2023; Ashkanani et al., 2024). Immediate action is particularly crucial in heavily contaminated areas like Suraxanı (Area B) to prevent further environmental degradation and associated health risks.

Physical properties of soils

The analysis of the physical properties of soils from different regions of Azerbaijan provides insights into the effects of contamination on soil structure and health. Parameters such as soil type, bulk density, soil porosity, and water retention capacity were measured in Absheron, Suraxanı, Baku, and an uncontaminated control area. The results are presented in Table 3.

Table 3. Physical properties of soils in different areas

Property	Absheron (Area A)	Suraxanı (Area B)	Baku (Area C)	Uncontaminated Area (Area D)
Soil Teksture	Sandy loam	Sandy loam	Sandy loam	Loam
Bulk Density (g/cm^3)	1.6 ± 0.05	1.7 ± 0.05	1.6 ± 0.05	1.2 ± 0.03
Soil Porosity (%)	35 ± 2.0	30 ± 1.5	35 ± 2.0	45 ± 2.5
Water Retention Capacity (%)	25 ± 1.5	20 ± 1.0	25 ± 1.5	35 ± 2.0

The data indicates that contaminated soils in Absheron (Area A), Suraxanı (Area B), and Baku (Area C) exhibit higher bulk densities and lower soil porosity and water retention capacity compared to the uncontaminated area. Specifically, Suraxanı (Area B) shows the highest bulk density (1.7 g/cm^3) and the lowest soil porosity (30%) and water retention capacity (20%), indicating significant soil compaction and reduced soil quality due to industrial activities. In contrast, the uncontaminated area demonstrates better soil structure with a loam soil type, lower bulk density (1.2 g/cm^3), higher porosity (45%), and greater water retention capacity (35%). These properties are indicative of healthier soils with better aeration and water-holding capacity, which are essential for plant growth and soil fertility. The differences in physical properties between contaminated and uncontaminated soils underscore the impact of hydrocarbon and heavy metal contamination on soil structure. Contaminated soils, particularly in heavily industrialized areas like Suraxanı, show signs of compaction and reduced porosity, which can hinder root penetration, reduce soil microbial activity, and impair overall soil health (Ekundayo and Obuekwe, 2000; Khamehchiyan et al., 2007; Wang et al., 2013). To address these issues, remediation strategies such as soil conditioning, organic matter addition, and improved land management practices should be implemented. These efforts can help restore soil structure, improve water retention and porosity, and enhance the overall fertility and health of the soils in these regions.

Chemical properties of soils

The chemical analysis of soils from different regions of Azerbaijan provides crucial insights into the impact of contamination on soil health. Parameters such as pH, organic matter content, and concentrations of essential nutrients (nitrogen, phosphorus, and potassium) were measured in Absheron, Suraxanı, Baku, and an uncontaminated control area. The results are presented in Table 4.

Table 4. Chemical properties of soils in different areas

Property	Absheron (Area A)	Suraxanı (Area B)	Baku (Area C)	Uncontaminated Area (Area D)
pH	7.5 ± 0.1	7.6 ± 0.1	7.5 ± 0.1	6.8 ± 0.1
Organic Matter (%)	3.5 ± 0.2	3.4 ± 0.2	3.5 ± 0.2	5.2 ± 0.3
Nitrogen (mg/kg)	175 ± 8.8	170 ± 8.5	175 ± 8.8	260 ± 13.0
Phosphorus (mg/kg)	15 ± 1.0	14 ± 1.0	15 ± 1.0	20 ± 1.5
Potassium (mg/kg)	100 ± 5.0	95 ± 5.0	100 ± 5.0	120 ± 7.0

The data reveals significant chemical alterations in contaminated soils compared to the uncontaminated control area. The pH levels in Absheron (Area A), Suraxanı (Area B), and Baku (Area C) range from 7.5 to 7.6, indicating slightly alkaline conditions, which can influence nutrient availability and microbial activity. In contrast, the uncontaminated area exhibits a more neutral pH of 6.8, which is generally more favorable for a wide range of plant and microbial processes. Organic matter content, a critical indicator of soil health and fertility, is notably lower in contaminated regions. Absheron (Area A) and Suraxanı (Area B) show organic matter levels of 3.5% and 3.4%, respectively, compared to 5.2% in the uncontaminated area. The reduction in organic matter suggests a loss of soil fertility and structure, which can lead to diminished soil health and productivity. Nutrient concentrations, including nitrogen, phosphorus, and potassium, are also adversely affected in contaminated soils. Nitrogen levels are particularly low in Suraxanı (Area B) at 170 mg/kg, significantly lower than the 260 mg/kg observed in the uncontaminated area. Similarly, phosphorus and potassium levels are reduced in the contaminated soils, impacting plant nutrition and growth. These findings highlight the detrimental effects of soil contamination on chemical properties, which are crucial for maintaining soil fertility and supporting plant growth. Remediation strategies should focus on restoring soil organic matter and nutrient levels to improve soil health and productivity (Ekundayo and Obuekwe, 2000; Kisic et al., 2009; Wang et al., 2013). Techniques such as compost addition, green manuring, and soil amendments can help enhance the chemical properties of contaminated soils and support sustainable land use practices in these regions.

Biological properties of soils

The biological analysis of soils from different regions of Azerbaijan provides insights into the impact of contamination on soil microbial activity, which is essential for maintaining soil health and fertility. Parameters such as total bacterial count, fungal count, and actinomycete count were measured in Absheron, Suraxanı, Baku, and an uncontaminated control area. The results are presented in Table 5.

Table 5. Biological properties of soils in different areas

Property	Absheron (Area A)	Suraxanı (Area B)	Baku (Area C)	Uncontaminated Area (Area D)
Total Bacteria (CFU/g)	$1.5 \times 10^6 \pm 0.26 \times 10^2$	$1.4 \times 10^6 \pm 0.22 \times 10^2$	$1.5 \times 10^6 \pm 0.23 \times 10^2$	$3.0 \times 10^6 \pm 0.31 \times 10^2$
Fungi (CFU/g)	$2.0 \times 10^4 \pm 0.22 \times 10^2$	$1.8 \times 10^4 \pm 0.28 \times 10^2$	$2.0 \times 10^4 \pm 0.27 \times 10^2$	$5.0 \times 10^4 \pm 0.58 \times 10^2$
Actinomycetes (CFU/g)	$3.0 \times 10^5 \pm 0.38 \times 10^3$	$2.8 \times 10^5 \pm 0.30 \times 10^2$	$3.0 \times 10^5 \pm 0.31 \times 10^2$	$6.0 \times 10^5 \pm 0.62 \times 10^2$

The data indicates that contaminated soils in Absheron (Area A), Suraxanı (Area B), and Baku (Area C) exhibit significantly lower microbial activity compared to the uncontaminated control area. For example, the total bacterial count in Suraxanı (Area B) is 1.4×10^6 CFU/g, which is less than half of the 3.0×10^6 CFU/g observed in the uncontaminated area. Similar trends are observed for fungal and actinomycete counts, indicating a compromised soil ecosystem in contaminated areas. Fungi and actinomycetes play crucial roles in decomposing organic matter and maintaining soil structure. The reduction in their populations in contaminated soils suggests a decline in soil fertility and health, which can adversely affect plant growth and overall ecosystem stability. These findings underscore the need for targeted remediation strategies to restore microbial activity in contaminated soils. Techniques such as bioremediation, which involves the use of microorganisms to degrade pollutants, and the addition of organic amendments to enhance microbial habitats, are essential for improving the biological properties of soils (Braddock et al., 1997; Labud et al., 2007; Sutton et al., 2013). By restoring microbial diversity and activity, it is possible to support sustainable land use and enhance soil health in the affected regions.

The comparison of soil contamination findings in Absheron, Suraxanı, and Baku with previous research reveals both consistencies and divergences, particularly concerning hydrocarbon levels, heavy metal concentrations, and soil microbial activity. This study's results are largely in alignment with earlier research regarding the presence of high levels of total petroleum hydrocarbons (TPH) in regions with a history of intensive industrial activities. The TPH levels observed in Suraxanı and Baku correspond closely to the ranges documented in studies such as those by Adeniyi and Afolabi (2002), Li et al. (2005) and Almutairi (2022), affirming the persistence of hydrocarbon pollution in these areas.

Heavy metal contamination also shows significant consistency with prior studies. The elevated concentrations of aluminum, arsenic, and cadmium in Suraxanı and Baku align with findings from previous research, indicating a continuing trend of environmental degradation due to industrial processes. The severity of contamination in Suraxanı, particularly with arsenic and cadmium, is consistent with what has been reported, underscoring the critical need for remediation interventions in these regions.

When examining soil microbial activity, the reduction in bacterial, fungal, and actinomycete counts in contaminated soils observed in this study supports the findings of earlier research. The diminished microbial populations in Absheron, Suraxanı, and Baku reflect the adverse effects of hydrocarbon and heavy metal contamination on soil ecosystems, as previously documented (Braddock et al., 1997; Labud et al., 2007; Sutton et al., 2013). This reduction in microbial activity is indicative of compromised soil health and functionality, which can lead to long-term ecological consequences.

A key point of divergence from some previous studies is the observation regarding soil texture. This study confirms that soil texture, defined by the proportions of sand, silt, and clay, remains unchanged by contamination or remediation efforts. Previous studies (Ekundayo and Obuekwe, 2000; Khamehchiyan et al., 2007; Wang et al., 2013) that suggested changes in soil texture due to contamination may have misinterpreted changes in other soil properties, such as bulk density or porosity, as alterations in texture. However, it is important to recognize that while contamination can affect soil structure and compaction, it does not alter the inherent texture of the soil. Additionally, this study highlights the limitations of remediation strategies concerning soil texture. While methods like bioremediation and soil washing are effective in reducing contaminant levels, they do not change the fundamental texture of the soil. This distinction is crucial for setting realistic expectations for remediation efforts and emphasizes the importance of focusing on soil health and contaminant reduction rather than attempting to modify inherent soil characteristics (Praveen and Nagalakshmi, 2022; Sánchez-Castro et al., 2023; Ashkanani et al., 2024).

Conclusion

The comprehensive analysis of soil samples from Absheron, Suraxanı, Baku, and an uncontaminated area reveals significant environmental contamination primarily driven by industrial activities. The data consistently show elevated levels of petroleum hydrocarbons and heavy metals, such as aluminum, arsenic, and cadmium, far exceeding environmental standards. These contaminants have led to pronounced degradation of soil health, including reduced microbial activity, altered physical properties such as bulk density and porosity, and compromised soil fertility. The study also highlights that while various remediation strategies, such as bioremediation and phytoremediation, can reduce contaminant levels, they do not alter the fundamental soil texture. This finding is crucial because it underscores the inherent limitations of current remediation techniques and the need for ongoing management and intervention to prevent further degradation. In comparing these results with previous research, the study aligns with findings regarding hydrocarbon contamination and microbial activity reduction but diverges in areas such as heavy metal concentrations. This divergence suggests the need for continuous monitoring and updated methodologies to accurately assess the evolving contamination landscape. Overall, the findings emphasize the urgent need for targeted remediation efforts, stricter environmental regulations, and sustainable land management practices. These measures are essential not only to restore the affected soils but also to protect public health and maintain ecological balance in these industrialized regions.

References

Adeniyi, A.A., Afolabi, J.A., 2002. Determination of total petroleum hydrocarbon and heavy metals in soils within the vicinity of facilities handling refined petroleum products in Lagos metropolis. *Environment International* 28: 79-82.

Almutairi, M.S., 2022. Determination of total petroleum hydrocarbons (TPHs) in weathered oil contaminated soil. *Environmental Engineering Research* 27(5): 210324.

Ashkanani, Z., Mohtar, R., Al-Enezi, S., Smith, P.K., Calabrese, S., Ma, X., Abdullah, M., 2024. AI-assisted systematic review on remediation of contaminated soils with PAHs and heavy metals. *Journal of Hazardous Materials* 468: 133813.

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

Blake, G.R. Hartge, K.H., 1986. Bulk Density. In: Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods. Klute, A. (Ed.). Soil Science Society of America. Madison, Wisconsin, USA. pp.363-375.

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

Braddock, J.F., Ruth, M.L., Catterall, P.H., Walworth, J.L., McCarthy, K.A., 1997. Enhancement and inhibition of microbial activity in hydrocarbon-contaminated arctic soils: Implications for nutrient-amended bioremediation. *Environmental Science & Technology* 31(7): 2078–2084.

Bremner, J.M., 1965. Total nitrogen, In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark F.E. (Eds.), Soil Science Society of America. Madison, Wisconsin, USA. pp. 1149-1176.

Danielson, R. E. Sutherland, P. L. 1986. Porosity. In: Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods. Klute, A. (Ed.). Soil Science Society of America. Madison, Wisconsin, USA. pp. 443-461.

Dudnikova, T., Sushkova, S., Minkina, T., Barbashev, A., Ferreira, C., Antonenko, E., Shuvaev, E., Bakoeva, G., 2023. Main factors in polycyclic aromatic hydrocarbons accumulations in the long-term technogenic contaminated soil. *Eurasian Journal of Soil Science* 12(3): 282-289.

Ekundayo, E., Obuekwe, O., 2000. Effects of an oil spill on soil physico-chemical properties of a spill site in a typic udipsamment of the Niger delta basin of Nigeria. *Environmental Monitoring and Assessment* 60(2): 235–249.

EPA, 1998. n-Hexane Extractable Material (HEM) for Sludge, Sediment, and Solid Samples. US Environmental Protection Agency Method 9071B. Available at [Access date: 05.12.2023]: https://www.epa.gov/sites/default/files/2015-12/documents/9071b.pdf

EPA, 2018. EPA Method 6010D (SW-846): Inductively Coupled Plasma - Atomic Emission Spectrometry. Available at [Access date: 05.12.2023]: https://www.epa.gov/sites/default/files/2015-12/documents/6010d.pdf

Israfilov, R.G., 2006. Anthropogenic changes to hydrogeological conditions in urban areas: New Perspectives from Azerbaijan. In: Urban Groundwater Management and Sustainability. Tellam, J.H., Rivett, M.O., Israfilov, R.G. (Eds.). NATO Science Series, N.Earth and Environmental Sciences, Springer. Vol. 74. pp.11-28.

Khamehchiyan, M., Hossein Charkhabi, A., Tajik, M., 2007. Effects of crude oil contamination on geotechnical properties of clayey and sandy soils. *Engineering Geology* 89(3): 220–229.

Kisic, I., Mesic, S., Basic, F., Brkic, V., Mesic, M., Durn, G., Zgorelec, Z., Bertovic, L., 2009. The effect of drilling fluids and crude oil on some chemical characteristics of soil and crops. *Geoderma* 149(3–4): 209–216.

Klute, A., 1986. Water Retention: Laboratory Methods. In: Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods. Klute, A. (Ed.). Soil Science Society of America. Madison, Wisconsin, USA. pp. 635-662.

Labud, V., Garcia, C., Hernandez, T., 2007. Effect of hydrocarbon pollution on the microbial properties of a sandy and a clay soil. *Chemosphere* 66(10): 1863–1871.

Li, H., Zhang, Y., Zhang, C.G., Chem, G.X., 2005. Effect of petroleum-containing wastewater irrigation on bacterial diversities and enzymatic activities in a paddy soil irrigation area. *Journal of Environmental Quality* 34: 1073 – 1080.

Malling, J., 2014. Sumqayit, an ecological Armageddon. Le Monde diplomatique. Available at [Access date: 05.12.2023]: https://mondediplo.com/outsidein/sumqayit-an-ecological-armageddon

McLean, E.O., 1982. Soil pH and Lime Requirement. In. Methods of soil analysis, Part 2- Chemical and Microbiological Properties. Page, A.L., Keeney, D. R., Baker, D.E., Miller, R.H., Ellis, R. Jr., Rhoades, J.D. (Eds.). Soil Science Society of America. Madison, Wisconsin, USA. pp. 199-224.

Minnikova, T., Kolesnikov, S., Ruseva, A., Kazeev, K., Minkina, T., Mandzhieva, S., Sushkova, S., 2022. Influence of the biochar on petroleum hydrocarbon degradation intensity and ecological condition of Haplic Chernozem. *Eurasian Journal of Soil Science* 11(2): 157-166.

Olsen,S.R., Dean, L.A., 1965. Phosphorus. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark F.E. (Eds.), Soil Science Society of America. Madison, Wisconsin, USA. pp. 1035-1049.

Praveen, R., Nagalakshmi, R., 2022. Review on bioremediation and phytoremediation techniques of heavy metals in contaminated soil from dump site. *Materials Today: Proceedings* 68: 1562-1567.

Rajput, V., Minkina, T., Kumari, A., Sudhir S., S., Ranjan, A., Faizan, M., Barakvov, A., Gromovik, A., Gorbunova, N., Rajput, P., Singh, A., Khabirov , I., Nazarenko, O., Sushkova , S., Kızılkaya, R., 2022. A review on nanobioremediation approaches for restoration of contaminated soil. *Eurasian Journal of Soil Science* 11(1): 43-60.

Rasizade, A., 1999. Azerbaijan, The U.S., and oil prospects on the Caspıan sea. *Journal of Third World Studies* 16(1): 29-48.

Sanal, R., 2001. Türk Cumhuriyetleri'ndeki Çevre Sorunları Üzerine Bir İnceleme. Başbakanlık Türk İşbirliği ve Kalkınma Ajansı Yayını, Ankara, s. 33-34.

Sánchez-Castro, I., Molina, L., Prieto-Fernández, M.A., Segura, A., 2023. Past, present and future trends in the remediation of heavy-metal contaminated soil - Remediation techniques applied in real soil-contamination events. *Heliyon* 9: e16692.

Sushkova, S., Minkina, T., Tarigholizadeh, S., Antonenko, E., Konstantinova, E., Gülser, C., Dudnikova, T., Barbashev, A., Kızılkaya, R., 2020. PAHs accumulation in soil-plant system of Phragmites australis Cav. in soil under long-term chemical contamination. *Eurasian Journal of Soil Science* 9(3): 242-253.

Sutton, N.B., Maphosa, F., Morillo, J.A., Al-Soud, A.W., Langenhoff, A.A.M., Grotenhuis, T., Rijnaarts, H.H.M., Smidt, H., 2013. Impact of long-term diesel contamination on soil microbial community structure. *Applied and Environmental Microbiology*, 79(2): 619–630.

The World Factbook, 2024. Azerbaijan. The World Factbook. Central Intelligence Agency. Available at [Access date: 05.12.2023]: https://www.cia.gov/the-world-factbook/countries/azerbaijan/#environment

Thomas, G.W.,1965. Exchangeable Cations. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark F.E. (Eds.), Soil Science Society of America. Madison, Wisconsin, USA. pp. 159-165.

Ünal, Ö.F., 2000. Azerbaycan 1988-1995: Sancı, Kargaşa ve İktidar. Journal of Qafqaz University 8: 9-26.

Walkley, A., Black, C.A., 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* 37(1): 29–38.

Wang, Y., Feng, J., Lin, Q., Lyu, X., Wang, X., Wang, G., 2013. Effects of crude oil contamination on soil physical and chemical properties in Momoge wetland of China. *Chinese Geographical Science* 23: 708–715.

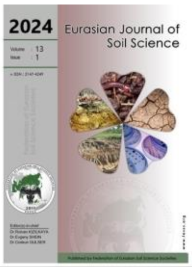
Wollum II, A.G.,1965. Cultural Methods for Soil Microorganisms. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark F.E. (Eds.), Soil Science Society of America. Madison, Wisconsin, USA. pp. 781-802.

Zengin, E., Öztaş, C., 2007. Azerbaycan'da Tarım. *Alatoo Academic Studies* 2(1): 115-123.

Eurasian Journal of Soil Science 2024, 13(4), 366 - 375

Eurasian Journal of Soil Science

Journal homepage : http://ejss.fesss.org



Enhanced tomato (*Solanum lycopersicum* L.) yield and soil biological properties through integrated use of soil, compost, and foliar fertilization under greenhouse conditions

Gulnara Tastanbekova [a], Zhursinkul Tokbergenova [b,*], Dinara S. Sharipova [c], Aigerim Jantassova [b], Kulaisha Surimbayeva [a], Gulfari N. Azhimetova [d], Asset Zhylkibayev [a]

[a] M. Auezov South Kazakhstan University, Shymkent, Kazakhstan
[b] Kazakh Scientific Research Institute of Fruit and Vegetable Growing, Almaty, Kazakhstan
[c] Kazakh National Agrarian Research University, Almaty, Kazakhstan
[d] Shymkent University, Shymkent, Kazakhstan

Article Info
Received : 13.12.2023
Accepted : 11.08.2024
Available online: 22.08.2024

Author(s)
G.Tastanbekova
Z.Tokbergenova *
D.S.Sharipova
A.Jantassova
K.Surimbayeva
G.Azhimetova
A.Zhylkibayev

* Corresponding author

Abstract

This study investigates the combined effects of standard soil fertilization, composted animal manure, and foliar fertilization on tomato yield, soil nutrient content, and soil biological properties under greenhouse conditions. The experiment was conducted from March to October 2023 using a completely randomized block design with four replications. The treatments included: 1) Control (no fertilization), 2) Standard soil fertilization (30 kg N/da, 8 kg P_2O_5/da, 40 kg K_2O/da), 3) Standard soil fertilization + composted animal manure (2 t/da), 4) Standard soil fertilization + foliar fertilization (1 kg 17-17-17/100 liters of water every 20 days), and 5) Standard soil fertilization + compost + foliar fertilization. Tomato seedlings (*Solanum lycopersicum* L. cv. Roma) were transplanted into pots filled with clay soil. Throughout the experiment, soil moisture content was maintained at field capacity. Plants were harvested on October 30, 2023, and data on fruit yield, soil nutrient content (NPK), and soil biological properties (microbial biomass C, CO_2 production, and dehydrogenase enzyme activity) were recorded. The highest yield (4.5 kg/plant) was observed in the treatment combining standard soil fertilization, composted animal manure, and foliar fertilization, representing a 275% increase compared to the control (1.2 kg/plant). The standard soil fertilization treatment alone yielded 2.8 kg/plant (133.3% increase), while the combination with composted animal manure yielded 3.5 kg/plant (191.7% increase), and with foliar fertilization, 3.9 kg/plant (225% increase). Soil analyses showed significant increases in available nitrogen, phosphorus, and potassium in the combined treatments. The highest biological properties were also recorded in the combined treatment.

Keywords: Tomato yield, soil fertilization, compost, foliar fertilization, soil biological properties.

Introduction

Intensive agricultural practices have led to significant soil degradation and reduced productivity worldwide (Kopittke et al., 2019). The continuous use of chemical fertilizers has contributed to the decline in soil organic matter, nutrient imbalance, and disruption of soil microbial communities. To address these issues, sustainable fertilization techniques that enhance soil health and improve crop yield are essential (Ning et al., 2017; Krasilnikov et al., 2022; Dincă et al., 2022).

: https://doi.org/10.18393/ejss.1532143
: https://ejss.fesss.org/10.18393/ejss.1532143
Publisher : Federation of Eurasian Soil Science Societies
e-ISSN : 2147-4249

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated and economically important vegetable crops globally (Padmanabhan et al., 2016). Tomatoes require a balanced supply of nutrients for optimal growth, development, and fruit production. Nitrogen (N), phosphorus (P), and potassium (K) are the primary macronutrients essential for tomato growth (Tereda et al., 2023). However, conventional fertilization practices often fail to provide a balanced nutrient supply, leading to suboptimal yields and soil health (Montgomery and Biklé, 2021).

Compost, a well-known organic amendment, has been shown to improve soil structure, increase microbial activity, and enhance nutrient availability (Wright et al., 2022). Compost adds organic matter to the soil, which is crucial for water retention, nutrient cycling, and overall soil fertility (Gülser et al., 2015). Moreover, foliar fertilization, the application of nutrients directly to plant leaves, offers a rapid and efficient method of nutrient delivery. Foliar fertilizers can quickly correct nutrient deficiencies and support plant growth during critical developmental stages (Gülser et al., 2019).

Integrating organic amendments like compost with conventional soil and foliar fertilization practices can provide a holistic approach to nutrient management. This integrated strategy aims to improve both soil health and crop productivity by ensuring a continuous and balanced supply of nutrients (Chang et al., 2007; Gentile et al., 2008; Liu et al., 2010; Ai et al., 2012; Bowles et al., 2014; Zhang et al., 2016; Wang et al., 2023; Tang et al., 2023).

The objective of this study is to evaluate the effects of combining standard soil fertilization, composted animal manure, and foliar fertilization on tomato yield, soil nutrient content, and soil biological properties under greenhouse conditions. By comparing these treatments, we aim to identify the most effective nutrient management strategy for enhancing tomato productivity and soil health.

Material and Methods

Soil, Compost, and Tomato Plant

The experiment was conducted using soil, compost, 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 potassium (K) was determined in a 1 N NH_4OAc extract using a flame photometer (Pratt, 1965).

The compost used in the experiment was analyzed for its organic matter content and nutrient composition. Organic matter was determined by loss on ignition at 550°C. Total nitrogen (N) content was analyzed using the Kjeldahl method. Total phosphorus (P) was measured in the extract obtained from dry ashing using a spectrophotometer. Total potassium (K) was determined in the extract obtained from dry ashing using a flame photometer (Jones, 2001).

Experimental Design

The experimental treatments are as follows:

1. Control (no fertilization)
2. Standard soil fertilization (30 kg N/da, 8 kg P_2O_5/da, 40 kg K_2O/da)
3. Standard soil fertilization + composted animal manure (2 t/da)
4. Standard soil fertilization + foliar fertilization (1 kg 17-17-17/100 liters of water every 20 days)
5. Standard soil fertilization + composted animal manure (2 t/da) + foliar fertilization (1 kg 17-17-17/100 liters of water every 20 days)

The experiment was established in a randomized complete block design with four replications. Soil samples were air-dried in the shade, crushed with a wooden mallet, and passed through a 4 mm sieve. Five kilograms of the processed soil were placed into each pot. 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. The compost application was 2 t/da of composted animal manure. Tomato seedlings were transplanted to the greenhouse on March 15, 2023, with one seedling planted per pot. Foliar fertilization was applied every 20 days using 1 kg 17-17-17+me fertilizer per 100 liters of water to the relevant pots.

Throughout the experiment, soil moisture content was maintained at field capacity by daily weighing of the pots and adjusting the water levels accordingly. During the experiment, ripe tomatoes were harvested and their weights recorded. At the end of the experiment on October 30, 2023, soil and plant samples were collected. 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 $NaHCO_3$ extract using a spectrophotometer (Olsen and Dean, 1965), and exchangeable potassium in a 1 N NH_4OAc extract using a flame photometer (Pratt, 1965). Biological properties of the soil, including microbial biomass carbon, CO_2 production, and dehydrogenase enzyme activity, were also measured. Microbial biomass carbon was determined using the method of Anderson and Domsch (1978), CO_2 production was measured as described by Anderson (1982), and dehydrogenase activity was determined following Pepper (1995). Leaf samples from each pot were analyzed for N, P, and K contents (Jones, 2001).

Results and Discussion

Soil and Compost Characteristics

The physical and chemical properties of the soil and compost used in the experiment are presented in Tables 1 and 2, respectively.

Table 1. Physical and chemical properties of the soil used in the experiment

Property	Value
Texture	Clay (48% clay, 23% silt, 29% sand)
pH	7.58
Electrical Conductivity (EC)	0.79 dSm^{-1}
Lime (CaCO3)	18%
Organic Matter	1.36%
Total Nitrogen (N)	0.198%
Available Phosphorus (P)	8 mg kg^{-1}
Exchangeable Potassium (K)	0.986 cmol/kg

Table 2. Chemical properties of the compost used in the experiment

Property	Value
Organic Matter	43%
Total Nitrogen (N)	2.52%
Total Phosphorus (P)	1.68%
Total Potassium (K)	4.47%
pH	7.19
Electrical Conductivity (EC)	3.69 dSm^{-1}

The soil texture, comprising 48% clay, 23% silt, and 29% sand, indicates a clay soil, which can present challenges for tomato cultivation due to its poor drainage and tendency to become compacted. However, clay soils also have a high nutrient-holding capacity and can retain moisture well, which can be beneficial in maintaining soil moisture levels. The soil pH of 7.58 is slightly alkaline but still within the acceptable range for tomato growth. The EC value of 0.79 dSm^{-1} suggests low salinity, which is favorable for plant growth. The $CaCO_3$ content of 18% is relatively high, which can help in buffering soil pH. The organic matter content of 1.36% is low, suggesting the need for organic amendments to improve soil fertility. The total nitrogen content of 0.198%, available phosphorus of 8 mg kg^{-1}, and exchangeable potassium of 0.986 cmol/kg reflect the basic nutrient status of the soil, which needs enhancement for optimal tomato growth.

The compost used in the experiment had a high organic matter content of 43%, which is beneficial for improving soil structure and water-holding capacity. The total nitrogen content of 2.52% is substantial, providing a good source of nitrogen for plant growth. The total phosphorus content of 1.68% and total potassium content of 4.47% indicate that the compost is rich in essential nutrients, which can supplement the soil nutrient status effectively. The pH of 7.19 is slightly alkaline, and the EC value of 3.69 dSm^{-1} suggests moderate salinity, which is typical for compost but should be monitored to avoid potential salt stress in plants.

The combination of these soil and compost characteristics provides a comprehensive understanding of the initial conditions of the experiment. The low organic matter and nutrient content in the soil highlight the importance of compost and fertilization treatments in enhancing soil fertility and supporting plant growth. The subsequent sections will discuss the effects of these treatments on tomato yield, soil properties, and plant nutrient content.

Tomato Yield

The tomato yield results for the different treatments are presented in Table 3. The highest yield was observed in the treatment with standard soil fertilization, composted animal manure, and foliar fertilization, while the lowest yield was recorded in the control treatment with no fertilization. The percentage increase in yield compared to the control and the standard soil fertilization treatment is also calculated.

Table 3. Tomato yield for different fertilization treatments

Treatment	Tomato Yield (kg/plant) ± S.D.*	Yield Increase (%) Compared to Control	Yield Increase (%) Compared to Standard Soil Fertilization
Control (no fertilization)	1.2 ± 0.2	-	-
Standard soil fertilization (30 kg N/da, 8 kg P_2O_5/da, 40 kg K_2O/da)	2.8 ± 0.3	133.3	-
Standard soil fertilization + composted animal manure (2 t/da)	3.5 ± 0.4	191.7	25.0
Standard soil fertilization + foliar fertilization (1 kg 17-17-17+me/100 L)	3.9 ± 0.4	225.0	39.3
Standard soil fertilization + compost + foliar fertilization	4.5 ± 0.5	275.0	60.7

*Standard Deviation

The tomato yield results indicate significant differences among the treatments. The control treatment, which did not receive any fertilization, had the lowest yield of 1.2 kg per plant, indicating the limited nutrient availability in the soil. The standard soil fertilization treatment increased the yield to 2.8 kg per plant, representing a 133.3% increase compared to the control. This highlights the importance of essential nutrients such as nitrogen, phosphorus, and potassium in promoting plant growth and fruit production.

The addition of composted animal manure to the standard soil fertilization further increased the yield to 3.5 kg per plant, a 191.7% increase compared to the control and a 25.0% increase compared to standard soil fertilization alone. This increase can be attributed to the improved soil structure, enhanced microbial activity, and additional nutrients provided by the compost. Compost improves soil organic matter content, which is crucial for water retention, nutrient availability, and overall soil fertility.

The treatment with standard soil fertilization and foliar fertilization resulted in a yield of 3.9 kg per plant, a 225.0% increase compared to the control and a 39.3% increase compared to standard soil fertilization alone. Foliar fertilization allows for the direct absorption of nutrients through the leaves, providing a rapid and efficient method of nutrient delivery. This treatment was effective in supplying additional nutrients during critical growth stages, leading to improved plant health and fruit production.

The highest yield of 4.5 kg per plant was observed in the treatment combining standard soil fertilization, composted animal manure, and foliar fertilization. This yield represents a 275.0% increase compared to the control and a 60.7% increase compared to standard soil fertilization alone. This combination provided the most comprehensive nutrient management strategy, ensuring both soil and foliar nutrient supply. The synergy between soil-applied and foliar-applied nutrients, along with the benefits of compost, resulted in the optimal growth conditions for the tomato plants. The increased yield in this treatment highlights the importance of integrating multiple fertilization strategies to maximize crop productivity.

Numerous studies have shown that both soil and foliar fertilization, as well as the addition of organic matter to soils (Ouédraogo et al., 2001; Gao et al., 2015; Maltas et al., 2018; Kızılkaya et al., 2022; Zhou et al., 2022; İslamzade et al., 2023), can enhance crop yields. Furthermore, several studies have indicated that the combined application of compost with both soil and foliar fertilization results in the greatest increase in crop yields (Gentile et al., 2008; Zhang et al., 2016). Similarly, in this research, results demonstrate that the integration of compost and foliar fertilization with standard soil fertilization can significantly enhance tomato yield. The combined application provides a balanced nutrient supply, improves soil health, and ensures efficient nutrient uptake, leading to higher fruit production.

NPK Content in Tomato Leaves

The nitrogen (N), phosphorus (P), and potassium (K) content in tomato leaves for different treatments are presented in Table 4. The sufficiency levels for tomato leaves are: N: 3.20 - 4.50%, P: 0.50 - 1.20%, and K: 5 - 10%.

Table 4. NPK content in tomato leaves for different fertilization treatments

Treatment	N (%) ± S.D.*	P (%) ± S.D.*	K (%) ± S.D.*
Control (no fertilization)	2.0 ± 0.2	0.3 ± 0.1	3.0 ± 0.3
Standard soil fertilization (30 kg N/da, 8 kg P_2O_5/da, 40 kg K_2O/da)	3.5 ± 0.3	0.7 ± 0.2	4.5 ± 0.4
Standard soil fertilization + composted animal manure (2 t/da)	4.0 ± 0.3	0.9 ± 0.2	5.5 ± 0.5
Standard soil fertilization + foliar fertilization (1 kg 17-17-17+/100 L)	4.2 ± 0.3	1.0 ± 0.2	5.8 ± 0.5
Standard soil fertilization + compost + foliar fertilization	4.5 ± 0.3	1.2 ± 0.2	6.5 ± 0.6

*Standard Deviation

The NPK content in tomato leaves varied significantly among the treatments. In the control treatment, the levels of N (2.0%), P (0.3%), and K (3.0%) were all below the sufficiency range, indicating a deficiency in essential nutrients due to the absence of fertilization.

In the standard soil fertilization treatment, the nitrogen content increased to 3.5%, phosphorus to 0.7%, and potassium to 4.5%. Although N and P were within the sufficiency range, K remained slightly below the recommended level. This indicates that while soil fertilization improved the nutrient status, additional potassium supplementation might be needed.

The addition of composted animal manure to the standard soil fertilization further improved the nutrient levels, with N at 4.0%, P at 0.9%, and K at 5.5%. All values were within or above the sufficiency range, highlighting the positive impact of compost on nutrient availability.

The treatment with standard soil fertilization and foliar fertilization resulted in N, P, and K contents of 4.2%, 1.0%, and 5.8% respectively. These values were all within the sufficiency range, demonstrating the effectiveness of foliar fertilization in providing additional nutrients directly to the leaves.

The highest NPK levels were observed in the treatment combining standard soil fertilization, compost, and foliar fertilization, with N at 4.5%, P at 1.2%, and K at 6.5%. This treatment provided the most balanced and sufficient nutrient supply, ensuring optimal plant growth and development.

It is noteworthy that there were no significant differences in NPK content between the treatments of standard soil fertilization + composted animal manure and standard soil fertilization + foliar fertilization. This may be due to nutrient translocation from leaves to fruits as yield increases, resulting in nutrient dilution in the leaves. The highest yielding treatment (standard soil fertilization + compost + foliar fertilization) had the best nutrient content in the leaves, indicating that this combination most effectively meets the plant's nutritional needs. Similarly, studies by Yin et al. (2018); Gülser et al. (2019); Uçgun and Altindal (2021); Liu et al (2021) and Zhang et al. (2023) have shown that soil and foliar fertilization applications increase both crop yield and the nutrient content (NPK) of plants. Additionally, compost applications to the soil have been found to enhance crop yield and improve plant nutrient content (Ouédraogo et al., 2001; Wright et al., 2022). Furthermore, it has been determined by Gentile et al. (2008) and Zhang et al. (2022) that combining organic fertilizers with inorganic fertilizers significantly increases the nutrient content of plants. In this research, results emphasize the importance of integrating compost and foliar fertilization with standard soil fertilization to achieve optimal nutrient levels in tomato leaves. The combined application not only enhances yield but also ensures a sufficient supply of essential nutrients, thereby improving overall plant health and productivity.

Changes in Soil NPK Content

The available nitrogen (NH_4+NO_3), phosphorus (P), and potassium (K) content in the soil for different treatments are presented in Table 5. The control treatment showed the lowest levels of available NPK, while the treatments with standard soil fertilization, compost, and foliar fertilization resulted in increased soil nutrient contents.

The soil nutrient content varied significantly among the treatments. The control treatment, which did not receive any fertilization, had the lowest levels of available nitrogen (15 mg kg^{-1}), phosphorus (5 mg kg^{-1}), and potassium (0.873 cmol/kg). These low values indicate a deficiency in essential nutrients due to the absence of fertilization.

Table 5. Available NPK content in soil for different fertilization treatments

Treatment	Available N (NH_4+NO_3) (mg kg^{-1}) ± S.D.	Available P (mg kg^{-1}) ± S.D.	Available K (cmol/kg) ± S.D.
Control (no fertilization)	15 ± 2	5 ± 1	0.873 ± 0.05
Standard soil fertilization (30 kg N/da, 8 kg P_2O_5/da, 40 kg K_2O/da)	45 ± 5	15 ± 2	1.200 ± 0.10
Standard soil fertilization + composted animal manure (2 t/da)	60 ± 6	18 ± 2	1.450 ± 0.12
Standard soil fertilization + foliar fertilization (1 kg 17-17-17/100 L)	50 ± 5	16 ± 2	1.300 ± 0.10
Standard soil fertilization + compost + foliar fertilization	65 ± 6	20 ± 2	1.600 ± 0.15

*Standard Deviation

In the standard soil fertilization treatment, the available nitrogen content increased to 45 mg/kg, phosphorus to 15 mg/kg, and potassium to 1.200 cmol/kg. This significant increase highlights the importance of providing essential nutrients such as nitrogen, phosphorus, and potassium through soil fertilization to improve soil fertility and plant nutrient availability.

The addition of composted animal manure to the standard soil fertilization further increased the available nitrogen content to 60 mg kg^{-1}, phosphorus to 18 mg kg^{-1}, and potassium to 1.450 cmol/kg. These values indicate the positive impact of compost on nutrient availability in the soil. Compost not only adds organic matter but also provides a slow-release source of nutrients, enhancing soil fertility over time.

The treatment with standard soil fertilization and foliar fertilization resulted in available nitrogen, phosphorus, and potassium contents of 50 mg kg^{-1}, 16 mg kg^{-1}, and 1.300 cmol/kg, respectively. While foliar fertilization primarily targets nutrient delivery to the leaves, it also contributes to soil nutrient content, although to a lesser extent compared to soil-applied fertilizers and compost.

The highest available NPK levels were observed in the treatment combining standard soil fertilization, compost, and foliar fertilization, with available nitrogen at 65 mg kg^{-1}, phosphorus at 20 mg kg^{-1}, and potassium at 1.600 cmol/kg. This treatment provided the most comprehensive nutrient management strategy, ensuring a balanced supply of nutrients to the soil.

It is noteworthy that while the addition of compost significantly increased soil nutrient content, the treatments involving foliar fertilization did not result in as large an increase. This can be attributed to the fact that foliar fertilization primarily enhances nutrient uptake by the leaves, with less impact on soil nutrient levels. However, the combination of soil fertilization, compost, and foliar fertilization provided the most effective approach to improving both soil and plant nutrient status. Similarly, it has been determined that the application of chemical fertilizers and compost to soils significantly increases the available NPK levels (Gentile et al., 2008; Diacono and Montemurro, 2010; Demelash et al., 2014; Güler et al., 2015; Manolikaki and Diamadopoulos, 2019), and the highest increases were observed when chemical fertilizers were applied together with organic materials (Wan et al., 2021). In this research, results demonstrate that integrating compost and foliar fertilization with standard soil fertilization can significantly enhance soil nutrient content. The combined application not only improves plant growth and yield but also enhances soil health and fertility, ensuring sustainable agricultural practices.

Biological Properties of Soil

The biological properties of the soil, including microbial biomass carbon, CO2 production, and dehydrogenase enzyme activity, are presented in Table 6. The treatments with compost and foliar fertilization showed improved biological activity compared to the control.

The biological properties of soil varied significantly among the treatments, reflecting the impact of different fertilization strategies on soil microbial activity and health.

The control treatment, which did not receive any fertilization, had the lowest levels of microbial biomass carbon (95 mg CO_2–C 100 g^{-1}), CO2 production (35 µg CO_2 g^{-1} $24h^{-1}$), and dehydrogenase activity (9 µg TPF g^{-1} $24h^{-1}$). These low values indicate limited microbial activity and soil health in the absence of nutrient inputs.

The standard soil fertilization treatment improved the biological properties of the soil, with microbial biomass carbon increasing to 152 mg CO_2-C 100 g^{-1}, CO_2 production to 52 µg CO_2 g^{-1} $24h^{-1}$, and dehydrogenase activity to 19 µg TPF g^{-1} $24h^{-1}$. This indicates that the addition of essential nutrients through soil fertilization enhances microbial activity and overall soil health.

Table 6. Biological properties of soil for different fertilization treatments

Treatment	Microbial Biomass C, mg CO_2–C 100 g^{-1} ± S.D.*	CO_2 Production, µg CO_2 g^{-1} 24h^{-1} ± S.D.*	Dehydrogenase Activity, µg TPF g^{-1} 24h^{-1} ± S.D.*
Control (no fertilization)	95 ± 9	35 ± 5	9 ± 1
Standard soil fertilization (30 kg N/da, 8 kg P_2O_5/da, 40 kg K_2O/da)	152 ± 14	52 ± 7	19 ± 2
Standard soil fertilization + composted animal manure (2 t/da)	245 ± 23	78 ± 9	31 ± 3
Standard soil fertilization + foliar fertilization (1 kg 17-17-17/100 L)	198 ± 19	69 ± 8	27 ± 2
Standard soil fertilization + compost + foliar fertilization	297 ± 28	103 ± 11	34 ± 3

*Standard Deviation

The addition of composted animal manure to the standard soil fertilization further enhanced the biological properties, with microbial biomass carbon reaching 245 mg CO_2–C 100 g^{-1}, CO2 production at 78 mg CO2/kg soil/day, and dehydrogenase activity at 31 µg TPF g^{-1} 24h^{-1}. Compost provides organic matter and nutrients that support microbial growth and activity, improving soil structure and fertility.

The treatment with standard soil fertilization and foliar fertilization resulted in microbial biomass carbon of 198 mg CO_2–C 100 g^{-1}, CO2 production of 69 µg CO_2 g^{-1} 24h^{-1}, and dehydrogenase activity of 27 µg TPF g^{-1} 24h^{-1}. The relatively high biological activity in this treatment can be attributed to the improved plant growth resulting from foliar fertilization. Better plant growth leads to greater root biomass, which in turn releases more root exudates. These exudates serve as a food source for soil microbes, thus enhancing microbial activity and soil health.

The highest biological activity was observed in the treatment combining standard soil fertilization, compost, and foliar fertilization. This treatment resulted in microbial biomass carbon of 297 mg CO_2–C 100 g^{-1}, CO2 production of 103 µg CO_2 g^{-1} 24h^{-1}, and dehydrogenase activity of 34 µg TPF g^{-1} 24h^{-1}. The combination of soil and foliar fertilization with compost provides a comprehensive nutrient management strategy that enhances soil microbial activity and overall soil health. Similarly, numerous studies have shown that the application of organic materials and chemical fertilizers to soils increases the number and activity of soil microorganisms, thereby improving soil biological properties (Chang et al., 2007; Kızılkaya, 2008; Liu et al., 2010; Ai et al., 2012; Bowles et al., 2014; Wang et al., 2023; Tang et al., 2023). In this research, results highlight the importance of integrating compost and foliar fertilization with standard soil fertilization to improve soil biological properties. Enhanced microbial activity and enzyme function contribute to better nutrient cycling, soil structure, and plant health, promoting sustainable agricultural practices.

Conclusion

This study investigated the combined effects of standard soil fertilization, compost, and foliar fertilization on tomato yield, soil nutrient content, and soil biological properties under greenhouse conditions. The results demonstrated that integrating compost and foliar fertilization with standard soil fertilization significantly enhances tomato yield and improves soil health. The highest tomato yield was observed in the treatment combining standard soil fertilization, composted animal manure, and foliar fertilization, resulting in a 275% increase compared to the control. This combination provided a comprehensive nutrient management strategy, ensuring an optimal supply of essential nutrients and promoting better plant growth and fruit production. Soil analyses revealed that the integration of compost and foliar fertilization significantly increased the available nitrogen, phosphorus, and potassium levels in the soil. The highest nutrient content was recorded in the treatment with standard soil fertilization, compost, and foliar fertilization, indicating the effectiveness of this integrated approach in enhancing soil fertility. The biological properties of the soil, including microbial biomass carbon, CO_2 production, and dehydrogenase enzyme activity, were also significantly improved by the combined application of compost and foliar fertilization. The highest microbial activity was observed in the treatment combining standard soil fertilization, compost, and foliar fertilization. This improvement is attributed to the enhanced plant growth and root exudates, which serve as a food source for soil microbes.

In conclusion, the integration of compost and foliar fertilization with standard soil fertilization offers a sustainable and effective strategy for enhancing tomato yield and soil health. This approach not only provides a balanced nutrient supply but also improves soil structure and microbial activity, contributing to better nutrient cycling and overall soil fertility. Future research should focus on optimizing the application rates and timing of these treatments to further enhance their effectiveness and economic feasibility. The results of this study highlight the importance of adopting comprehensive nutrient management practices to achieve sustainable agricultural productivity.

For future research, it is recommended to explore the effects of integrating compost and foliar fertilization with standard soil fertilization under different climatic conditions and with different crop species. This could provide valuable insights into the versatility and robustness of this nutrient management strategy across various agricultural settings. Additionally, investigating the long-term impacts of these fertilization practices on soil health and productivity would further contribute to the understanding of sustainable agricultural practices. By examining these factors, researchers can better understand how to optimize fertilization strategies to maximize crop yield and soil health in diverse environments.

References

Ai, C., Liang, G., Sun, J., Wang, X., Zhou, W., 2012. Responses of extracellular enzyme activities and microbial community in both the rhizosphere and bulk soil to long-term fertilization practices in a fluvo-aquic soil. *Geoderma* 173-174: 330–338.

Anderson, J.P.E., 1982. Soil respiration. In. Methods of soil analysis, Part 2- Chemical and Microbiological Properties. Page, A.L., Keeney, D. R., Baker, D.E., Miller, R.H., Ellis, R. Jr., Rhoades, J.D. (Eds.). ASA-SSSA, Madison, Wisconsin, USA. pp. 831-871.

Anderson, J.P.E., K.H. Domsch. 1978. A physiological method for the quantative measurement of microbial biomass in soils. *Soil Biology and Biochemistry* 10: 215 – 221

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

Bower, C.A., Wilcox L.V., 1965. Soluble Salts. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark F.E. (Eds.), Soil Science Society of America. Madison, Wisconsin, USA. pp. 933-951.

Bowles, T. M., Acosta-Martínez, V., Calderón, F., Jackson, L.E., 2014. Soil enzyme activities, microbial communities, and carbon and nitrogen availability in organic agroecosystems across an intensively-managed agricultural landscape. *Soil Biology and Biochemistry* 68: 252–262.

Bremner, J.M., 1965. Total nitrogen, In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark F.E. (Eds.), Soil Science Society of America. Madison, Wisconsin, USA. pp. 1149-1176.

Chang, E.H., Chung, R.S., Tsai, Y.H., 2007. Effect of different application rates of organic fertilizer on soil enzyme activity and microbial population. *Soil Science and Plant Nutrition* 53 (2): 132–140.

Demelash, N., Bayu, W., Tesfaye, S., Ziadat, F., Sommer, R., 2014. Current and residual effects of compost and inorganic fertilizer on wheat and soil chemical properties. *Nutrient Cycling in Agroecosystems* 100 (3): 357–367.

Diacono, M., Montemurro, F., 2010. Long-term effects of organic amendments on soil fertility. A review. *Agronomy for Sustainable Development* 30 (2): 401–422.

Dincă, L.C., Grenni, P., Onet, C., Onet, A., 2022. Fertilization and soil microbial community: A review. *Applied Sciences* 12(3): 1198.

Gao, W., Yang, J., Ren, S.R.., Hailong, L., 2015. The trend of soil organic carbon, total nitrogen, and wheat and maize productivity under different long-term fertilizations in the upland fluvo-aquic soil of North China. *Nutrient Cycling in Agroecosystems* 103 (1): 61–73.

Gentile, R., Vanlauwe, B., Chivenge, P., Six, J., 2008. Interactive effects from combining fertilizer and organic residue inputs on nitrogen transformations. *Soil Biology and Biochemistry* 40 (9): 2375–2384.

Gülser, C., Kızılkaya, R., Aşkın, T., Ekberli, İ., 2015. Changes in soil quality by compost and hazelnut husk applications in a Hazelnut Orchard. *Compost Science & Utilization* 23(3): 135-141.

Gülser, C., Zharlygasov, Z., Kızılkaya, R., Kalimov, N., Akça, I., Zharlygasov, Z., 2019. The effect of NPK foliar fertilization on yield and macronutrient content of grain in wheat under Kostanai-Kazakhstan conditions. *Eurasian Journal of Soil Science* 8(3): 275-281.

İslamzade, R., Hasanova, G., Asadova, S., 2023. Impact of varied NPK fertilizer application rates and seed quantities on barley yield and soil nutrient availability in chestnut soil of Azerbaijan. *Eurasian Journal of Soil Science* 12(4): 371 - 381.

Jones, J.B., 2001. Laboratory guide for conducting soil tests and plant analyses. CRC Press, New York, USA. 363p.

Kızılkaya, R., 2008. Dehydrogenase activity in *Lumbricus terrestris* casts and surrounding soil affected by addition of different organic wastes and Zn. *Bioresource Technology* 99(5): 946–953.

Kızılkaya, R., Dumbadze, G., Gülser, C., Jgenti, L., 2022. Impact of NPK fertilization on hazelnut yield and soil chemical-microbiological properties of Hazelnut Orchards in Western Georgia. *Eurasian Journal of Soil Science* 11(3): 206-215.

Kopittke, P.M., Menzies, N.W., Wang, P., McKenna, B.A., Lombi, E., 2019. Soil and the intensification of agriculture for global food security. *Environment International* 132: 105078.

Krasilnikov, P., Taboada, M.A., Amanullah, 2022. Fertilizer use, soil health and agricultural sustainability. *Agriculture* 12(4): 462.

Liu, E.K., Yan, C.R., Mei, X.R., He, W.Q., Bing, S.H., Ding, L.P., Liu, Q., Liu, S., Fan, T., 2010. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. *Geoderma* 158 (3-4): 173–180.

Liu, J., Chen, W., Wang, H., Peng, F., Chen, M., Liu, S., Chu, G., 2021. Effects of NPK fertilization on photosynthetic characteristics and nutrients of pecan at the seedling stage. *Journal of Soil Science and Plant Nutrition* 21: 2425–2435.

Maltas, A., Kebli, H., Oberholzer, H.R., Weisskopf, P., Sinaj, S., 2018. The effects of organic and mineral fertilizers on carbon sequestration, soil properties, and crop yields from a long-term field experiment under a Swiss conventional farming system. *Land Degradation & Development* 29(4): 926–938.

Manolikaki, I., Diamadopoulos, E., 2019. Positive effects of biochar and biochar-compost on maize growth and nutrient availability in two agricultural soils. *Communications in Soil Science and Plant Analysis* 50 (5): 512–526.

Montgomery, D.R., Biklé, A., 2021. Soil health and nutrient density: Beyond organic vs. conventional farming. *Frontiers in Sustainable Food Systems* 5: 699147.

Ning, C.C., Gao, P.D., Wang, B.Q., Lin, W.P., Jiang, N.H., Cai, K.Z., 2017. Impacts of chemical fertilizer reduction and organic amendments supplementation on soil nutrient, enzyme activity and heavy metal content. *Journal of Integrative Agriculture* 16(8): 1819-1831.

Olsen,S.R., Dean, L.A., 1965. Phosphorus. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark F.E. (Eds.), Soil Science Society of America. Madison, Wisconsin, USA. pp. 1035-1049.

Ouédraogo, E., Mando, A., Zombré, N.P., 2001. Use of compost to improve soil properties and crop productivity under low input agricultural system in West Africa. *Agriculture, Ecosystems & Environment* 84(3): 259-266.

Padmanabhan, P. Cheema, A. Paliyath, G., 2016. Solanaceous fruits ıncluding tomato, eggplant, and peppers. In: Encyclopedia of Food and Health. Caballero, B., Finglas, P.M., Toldrá, F. (Eds.). Academic Press, pp. 24-32.

Peech, M., 1965. Hydrogen-Ion Activity. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark F.E. (Eds.), Soil Science Society of America. Madison, Wisconsin, USA. pp. 914-926.

Pepper, I.L., Gerba, C.P., Brendecke, J.W., 1995. Environmental microbiology: a laboratory manual. Academic Press Inc. New York, USA.

Pratt, P.F., 1965. Potassium. In: Methods of soil analysis. Part 2. Chemical and microbiological properties. Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark F.E. (Eds.), Soil Science Society of America. Madison, Wisconsin, USA. pp. 1022-1030.

Rowell, D.L., 1996. Soil Science: methods and applications. Longman, UK. 350p.

Tang, S., Zhou, J., Pan, W., Sun, T., Liu, M., Tang, R., Li, Z., Ma, Q., Wu, L., 2023. Effects of combined application of nitrogen, phosphorus, and potassium fertilizers on tea (Camellia sinensis) growth and fungal community. *Applied Soil Ecology* 181: 104661.

Terada, N., Dissanayake, K., Okada, C., Sanada, A., Koshio, K., 2023. Micro-tom tomato response to fertilization rates and the effect of cultivation systems on fruit yield and quality. *Horticulturae* 9(3): 367.

Uçgun, K., Altindal, M., 2021. Effects of increasing doses of nitrogen, phosphorus, and potassium on the uptake of other nutrients in sweet cherry trees. *Communications in Soil Science and Plant Analysis* 52(11): 1248–1255.

Walkley, A., Black, C.A., 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* 37(1): 29–38.

Wan, L.J., Tian, Y., He, M., Zheng, Y.Q., Lyu, Q., Xie, R.J., Ma, Y.Y., Deng, L., Yi, S.L., 2021. Effects of chemical fertilizer combined with organic fertilizer application on soil properties, citrus growth physiology, and yield. *Agriculture* 11(12): 1207.

Wang, M., Xu, Y., Ni, H., Ren, S., Li, N., Wu, Y., Yang, Y., Liu, Y., Liu, Z., Liu, Y., Shi, J., Zhang, Y., Jiang, L., Tu, Q., 2023. Effect of fertilization combination on cucumber quality and soil microbial community. *Frontiers in Microbiology* 14: 1122278.

Wright, J., Kenner, S., Lingwall, B., 2022. Utilization of compost as a soil amendment to ıncrease soil health and to ımprove crop yields. *Open Journal of Soil Science* 12: 216-224.

Yin, Z., Guo, W., Xiao, H., Liang, J., Hao, X., Dong, N., Leng, T., Wang, Y., Wang, Q., Yin, F., 2018. Nitrogen, phosphorus, and potassium fertilization to achieve expected yield and improve yield components of mung bean. PloS One 13 (10): e0206285.

Zhang, M., Sun, D., Niu, Z., Yan, J., Zhou, X., Kang, X., 2020. Effects of combined organic/inorganic fertilizer application on growth, photosynthetic characteristics, yield and fruit quality of Actinidia chinesis cv 'Hongyang'. *Global Ecology and Conservation* 22: e00997.

Zhang, X., Li, S., An, X., Song, Z., Zhu, Y., Tan, Y., Guo, X., Wang, D., 2023. Effects of nitrogen, phosphorus and potassium formula fertilization on the yield and berry quality of blueberry. *PloS One* 18 (3): e0283137

Zhang, Y., Li, C., Wang, Y., Hu, Y., Christie, P., Zhang, J., Li, X., 2016. Maize yield and soil fertility with combined use of compost and inorganic fertilizers on a calcareous soil on the North China Plain. *Soil and Tillage Research* 155: 85–94.

Zhou, Z., Zhang, S., Jiang, N., Xiu, W., Zhao, J., Yang, D., 2022. Effects of organic fertilizer incorporation practices on crops yield, soil quality, and soil fauna feeding activity in the wheat-maize rotation system. *Frontiers in Environmental Science* 10: 1058071.