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

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Abstract

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

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

Introduction

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

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

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

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

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

Material and Methods

Study Area

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

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

Soil Characteristics

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

Experimental Design and Treatments

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

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

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

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

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

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

Laboratory Analysis

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

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

Economic Analysis

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

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

Statistical Analysis

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

Results and Discussion

Tomato Yield Performance

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

Table 1. Effect of zeolite and fertilizers on tomato yield

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

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

Fruit Quality Parameters

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

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

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

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

Heavy Metal Mobility in Soil

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

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

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

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

Economic Efficiency of Treatments

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

Table 4. Economic efficiency of tomato production under different treatments

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

Conclusion

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

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

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

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References

Ahmed, S., Khan, M., Raza, T., Ahmad, R., Iqbal, J., Eash, N., 2022. Integrated use of bio-organic and chemical fertilizer to enhance yield and nutrients content of tomato. *Eurasian Journal of Soil Science* 11(2): 126-132.

Anas, M., Liao, F., Verma, K.K., Sarwar, M.A., Mahmood, A., Chen, Z.L., Li, Q., Zeng, X.P., Liu, Y., Li, Y.R., 2020. Fate of nitrogen in agriculture and environment: agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. *Biological Research* 53: 47.

Ay, A., Demirkaya, S., Kızılkaya, R., Gülser, C., 2022. The effects of two Fe-EDDHA chelated fertilizers on dry matter production and Fe uptake of tomato seedlings and Fe forms of a calcareous soil. *Eurasian Journal of Soil Science* 11(3): 259-265.

Bertalan-Balázs, B., Rahimi, M., Adelinia, A., Ebrahimi, E., Ojani, M., 2024. Impact assessment of Zeolite, Ca-bentonite and Biochar amendments on Cd bioavailability and fractions in polluted calcareous soils. *Environmental Earth Sciences* 83: 506.

Bihon, W., Ognakossan, K.E., Tignegre, J.B., Hanson, P., Ndiaye, K., Srinivasan, R., 2022. Evaluation of different tomato (*Solanum lycopersicum* L.) entries and varieties for performance and adaptation in Mali, West Africa. *Horticulturae* 8(7): 579.

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.

Choo, L.N.L.K., Ahmed, O.H., Talib, S.A.A., Ghani, M.Z.A., Sekot, S., 2020. Clinoptilolite zeolite on tropical peat soils nutrient, growth, fruit quality, and yield of *Carica papaya* L. cv. Sekaki. *Agronomy* 10(9): 1320.

Damian, F., Damian, G., Lăcătuşu, R., Postolache, C., Iepure, G., Jelea, M., Năsui, D., 2013. The heavy metals immobilization in polluted soils from romania by the natural zeolites use. *Carpathian Journal of Earth and Environmental Sciences* 8(4): 231–250.

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.

GOST 13192-73: Wines, wine materials and cognacs. Method for determination of sugar. Available at [Access date : 18.11.2024]: https://gostperevod.com/gost-13192-73.html

GOST 28561-90: Fruit and vegetable products. Methods for determination of total solids or moisture. Available at [Access date : 18.11.2024]: https://gostperevod.com/gost-28561-90.html

GOST 29270-95: Fruits, vegetables and derived products. Determination of nitrate content by potentiometric method. Available at [Access date : 18.11.2024]: https://gostperevod.com/gost-34570-2019.html

GOST 30178-96. Raw material and food-stuffs. Atomic absorption spectrometric method of determination of toxic elements. Available at [Access date : 18.11.2024]: https://gostperevod.com/gost-30178-96.html

Grandillo, S.; Zamir, D.; Tanksley, S.D., 1999. Genetic improvement of processing tomatoes: A 20 years perspective. *Euphytica* 110: 85–97.

HelgiLibrary, 2024. Tomato Production in Kazakhstan. Available at [Access date : 18.11.2024]: https://www.helgilibrary.com/indicators/tomato-production/kazakhstan/

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.

Javaid, A., Munir, N., Abideen, Z., Siddiqui, Z.S., Yong, J.W.H., 2024. The role of natural and synthetic zeolites as soil amendments for mitigating the negative impacts of abiotic stresses to improve agricultural resilience. *Plant Stress* 14: 100627.

Kavvadias, V., Ioannou, Z., Vavoulidou, E., & Paschalidis, C., 2023. Short term effects of chemical fertilizer, compost and zeolite on yield of lettuce, nutrient composition and soil properties. *Agriculture* 13(5): 1022.

Khamkure, S., Reyes-Rosas, A., González, A.Z., Samaniego-Moreno, L., Gamero-Melo, P., 2025. A sustainable approach to fertilizer management: Microwave-assisted synthesis of slow-release ammonium-natural clinoptilolite. *Sustainable Chemistry and Pharmacy* 45: 102004.

Maffia, A., Marra, F., Canino, F., Oliva, M., Mallamaci, C., Celano, G., Muscolo, A., 2023. Comparative study of fertilizers in tomato-grown soils: Soil quality, sustainability, and carbon/water footprints. *Soil Systems* 7(4): 109.

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.

Milošević, T., & Milošević, N., 2017. Influence of mineral fertilizer, farmyard manure, natural zeolite, and their mixture on fruit quality and leaf micronutrient levels of apple trees. *Communications in Soil Science and Plant Analysis* 48(5): 539–548.

Mohammed, E., Tewodros, M., Lulseged, T., Feyera, L., Wuletawu, A., Amsalu, T., 2024. Agronomic and socio-economic drivers of fertilizer use and crop productivity in smallholder wheat production systems in Ethiopia. *Discover Environment* 2: 130.

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.

Nakhli, S.A.A., Delkash, M., Bakhshayesh, B.E., Kazemian, H., 2017. Application of zeolites for sustainable agriculture: A review on water and nutrient retention. *Water, Air, & Soil Pollution* 228: 464.

Omer, E., Szlatenyi, D., Csenki, S., Alrwashdeh, J., Czako, I., Láng, V., 2024. Farming practice variability and its implications for soil health in agriculture: A review. *Agriculture* 14(12): 2114.

Rahmani, R., Khalesro, S., Heidari, G., Mokhatssi-Bidgoli, A., 2023. Vermicompost and zeolite improve yield, nutrient uptake, essential and fixed oil production, and composition of Nigella sativa L. *Frontiers in Sustainable Food Systems* 7: 1214691.

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.

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.

Shmelev, S.E., Salnikov, V., Turulina, G., Polyakova, S., Tazhibayeva, T., Schnitzler, T., Shmeleva, I.A., 2021. Climate change and food security: The impact of some key variables on wheat yield in Kazakhstan. *Sustainability* 13: 8583.

Sultanbayeva, G., Agatayeva, A. Kaiynbayeva, R., Kozhabekova, N. Chernyakova, R., Jussipbekov, U. 2022. Study of the sorption properties of natural zeolite in relation to Indium(III) and Gallium(III) cations on the model systems. *Crystals* 12(9): 1220.

Tastanbekova, G., Tokbergenova, Z., Sharipova, D., Jantassova, A., Surimbayeva, K., Azhimetova, G., Zhylkibayev, A., 2024. Enhanced tomato (Solanum lycopersicum L.) yield and soil biological properties through integrated use of soil, compost, and foliar fertilization under greenhouse conditions. *Eurasian Journal of Soil Science* 13(4): 366 - 375.

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.

Vassilina, T., Nasiyev, B., Shibikeyeva, A., Seitkali, N., Kossanov, S., 2024. The role of zeolite and mineral fertilizers in enhancing Table Beet (Beta vulgaris L.) productivity in dark chestnut soils of Southeast Kazakhstan. *Eurasian Journal of Soil Science* 13(4): 312 - 319.

Wea, T., Unonis, M., Khairuddin, M., Shaharuddin, S., Chai, N., 2018. Mechanism in using commercial high efficient zeolite-base greenfeed slow release fertilizers. *Journal of Agricultural Chemistry and Environment* 7: 1-9.