# Effect of Zeolite Soil Amendment on Soil Chemical Properties and Nitrogen Availability in Lettuce Production under South African Field Conditions

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**Abstract**

South Africa's vegetable sector is under increasing strain as soil degradation, water scarcity and climate variability affect sustainable crop production. This study evaluated the effects of zeolite application on selected soil chemical properties and mineral nitrogen dynamics in lettuce production under South African field conditions. A field experiment was conducted using a randomised complete block design with five zeolite application rates (0, 5, 10, 15, and 20 t. $ha^{-1}$) at ARC Infruitec-Nietvoorbij, Stellenbosch. Soil samples were collected before planting and after each harvest to analyse pH, cation exchange capacity (CEC), soil organic matter (SOM), soil organic carbon (SOC), exchangeable cations, plant-available phosphorus and potassium, and mineral nitrogen. Data were analysed using ANOVA, and treatment means were separated using Fisher's LSD test at $p \leq 0.05$. Zeolite significantly increased soil CEC. The highest value was 5.92 cmol. $kg^{-1}$ at 15 t $ha^{-1}$ in Season 1(S1), compared with 3.86 cmol. $kg^{-1}$ in the control. Total plant-available nitrogen (Mineral N) did not increase consistently with zeolite rate. It was higher in Season 2 (S2) than in S1. The control recorded the highest value in S2 (44.2 mg. $kg^{-1}$). The 10 t. $ha^{-1}$ rate recorded the lowest values in both seasons. SOM and SOC showed no significant treatment effects. Lettuce yield showed significant differences between seasons, but no significant treatment effect was observed. Zeolite was applied together with inorganic fertiliser. It increased soil CEC but did not raise mineral nitrogen consistently.

**Keywords:** clinoptilolite, soil conditioner, cation exchange capacity, nutrient retention, nitrate

## Introduction

Vegetable production in South Africa faces increasing challenges due to declining soil fertility, water scarcity, and climate variability, which threaten food security and the

productivity of smallholder farmers (Antoniadis et al., 2012; Mutengwa et al., 2023). Sustainable soil amendments are needed to improve nutrient use efficiency, increase nutrient availability, and support crop growth under these constraints (Farhan et al., 2024). Zeolite, a natural aluminosilicate mineral, has potential as a soil amendment due to its high cation exchange capacity, water-retention capacity, and ability to reduce nutrient leaching (Lal, 2012; Khan et al., 2024). Zeolite can also improve soil physical and chemical conditions by enhancing nutrient retention and influencing the availability of essential plant nutrients (Mondal et al., 2021; Szatanik-Kloc et al., 2021). Its negatively charged framework provides exchange sites that can retain positively charged nutrients, particularly $K^+$ and $NH_4^+$, thereby reducing their movement through the soil and potentially improving nutrient-use efficiency (Mumpton, 1999; n and Lal, 2023). Its porous structure and high ion-exchange capacity may contribute to improved nutrient-use efficiency and reduced nutrient losses, particularly in soils with low nutrient-retention capacity (Mumpton, 1999; Blanco and Lal 2023). Zeolite has a strong affinity for potassium ($K^+$) and ammonium ($NH_4^+$) ions, which it retains against leaching through ion exchange (Ahmad et al., 2025). Long-term benefits of zeolite application include sustained cation exchange capacity, reduced nutrient leaching over successive cropping seasons, and slow release of retained nutrients to crops (Legese et al., 2024).

Despite its benefits, the application of zeolite in South African vegetable production remains limited (Sindesi et al., 2026). Smallholder farmers predominantly rely on chemical fertilisers, which are costly and can exacerbate soil degradation through acidification, nutrient leaching, and reduced microbial activity (Mirzaei Aminiyan et al., 2015; Dimkpa et al., 2023). There is limited research on the effects of zeolite on soil chemical properties under field conditions, particularly over successive growing seasons, and its potential to improve nitrogen management and nutrient availability (Kavvadias et al., 2023). Previous studies have demonstrated that zeolite can influence soil exchangeable cations, cation exchange capacity, and nutrient availability, but responses may vary depending on soil characteristics, application rate, crop type, and duration of application (Sindesi et al., 2022; Sindesi et al., 2024). Evaluating these effects under South African field conditions could provide useful information on the suitability of zeolite as a sustainable soil amendment for vegetable production. This study therefore assessed the effect of different zeolite application rates on selected soil chemical properties and nitrogen management in vegetable production under field conditions.

## Materials and Methods

### Research Design and Site

A field trial was conducted at the ARC Infruitec-Nietvoorbij, Stellenbosch, Western Cape, South Africa, using a randomised complete block design (RCBD). Zeolite was applied at five rates (0, 5, 10, 15, and 20 t. $ha^{-1}$). It was incorporated into the soil before transplanting. Each treatment was replicated five times and included 30 plants. The mineralogical and chemical properties of the zeolite used in this study are presented in Table 2. Fertiliser applied at planting consisted of 79.2 g potassium chloride (KCl), 37.9 g single superphosphate (SSP), and 64.6 g urea per plot. Irrigation was supplied using a drip irrigation system with a discharge rate of 2.3 L. $h^{-1}$ to maintain adequate soil moisture throughout the

growing period. Lettuce seedlings were planted in the field, with a total of 750 plants established for the entire trial.

**Data Collection**

A composite soil sample was collected from the field for analysis of the initial soil chemical status (Table 1). At each harvest, soil chemical analysis was conducted. The soil samples were analysed using standard procedures outlined by the Non-affiliated Soil Analysis Work Committee (1990).

**Table 1.** *Baseline soil texture and chemical properties before zeolite application.*

| **Parameters** | **value** |
|---|---|
| Soil texture | Fine sandy loam |
| pH (KCl) | 6.3 |
| Available P (Bray II) (mg. $kg^{-1}$) | 82.2 |
| Available K (mg. $kg^{-1}$) | 178 |
| Carbon (%) | 1.45 |
| $NO_3^-N$ (mg. $kg^{-1}$) | 14.4 |
| $NH_4^+N$ (mg. $kg^{-1}$) | 6.2 |

**Table 2.** *Properties of zeolite*

| **Physical properties** | **Description** |
|---|---|
| Colour (Crude) | White to Grey |
| Appearance | Granules |
| Moisture (%) | < 15 |
| Loose bulk density (g. $cm^{-3}$) | 1.20 |
| Particle size distribution | 80% 1- 5 mm nominal (10% > 5 mm and 10% < 1 mm) |
| pH (30 g in 60 ml water) | 8-9 |
| CEC (cmol. $kg^{-1}$) | 16 |
| Water adsorption (on sinter plate) | 400% |
| Viscosity marsh funnel (seconds) | 21 |
| Surface Area (Bet method $m^2$. $g^{-1}$) | 43 |
| Average pore volume ($cm^3$. $g^{-1}$) | >0.10 |
| Average pore size (nm) | 7 |
| Specific gravity (g. $cm^{-3}$) | 2.51 |
| Chemical analysis | (%) Typical |
| $SiO_2$ | 64.30 |
| $Al_2O_3$ | 12.70 |
| $TiO_2$ | 0.10 |
| MgO | 1.30 |
| $Na_2O$ | 2.30 |
| $Fe_2O_3$ | 1.30 |
| CaO | 1.20 |
| $K_2O$ | 1.70 |
| Loss on ignition | 8.40 |
| Mineralogy | Approximate |
| %. Clinoptilolite | > 90 |
| %. Quartz | < 5 |

The parameters analysed included soil organic matter (SOM), soil organic carbon (SOC), total nitrogen (Total N), cation exchange capacity (CEC), plant-available phosphorus (P), plant-available potassium (K), dominant exchangeable cations ($Ca^{2+}$ , $K^{+}$ , $Mg^{2+}$ and $Na^{+}$ ), and soil pH (KCl) to evaluate the effects of zeolite application on soil chemical properties across the growing seasons. The two plant-available nitrogen types (ammonium-N ($NH_4^+$) and nitrate-N ($NO_3^-$ ) ) were added together to obtain Mineral N. Lettuce was harvested at maturity, nine weeks after planting. Fresh yield was recorded for each plot, and representative plant samples were oven-dried at 70 °C to constant weight to determine dry yield.

**Statistical Analysis**

Data were subjected to an analysis of variance (ANOVA) using SAS software version 9.4, SAS Institute Inc., Cary, NC, USA, 2000. Means were separated using Fisher's Least Significant Difference (LSD) test at $p \leq 0.05$ to determine significant differences among treatments.

**Discussion**

**Effect of zeolite on soil cation exchange capacity**

Soil CEC may be used as a good indicator of nutrient retention capacity. It directly influences the soil's ability to retain and supply important plant nutrients (Mondal et al., 2021). In this study, CEC increased with zeolite application, reaching a maximum at 15 t. $ha^{-1}$ in S1 (5.92 cmol. $kg^{-1}$) compared with the control (3.86 cmol. $kg^{-1}$), indicating an enhanced capacity for nutrient retention (Fig. 1). The control CEC was low. This agrees with the fine sandy loam texture of the site (Table 1), where clay content is limited (Ćirić et al., 2023). The increase in soil CEC with zeolite application may be attributed to the high surface area and negatively charged structure of zeolite, which provides additional exchange sites that enhance the soil's ability to retain nutrient cations such as $K^+$, $Ca^{2+}$ and $NH_4^+$ (Mumpton, 1999; Legese et al., 2024). These cations can be retained within the zeolite structure through ion-exchange processes and subsequently released gradually into the soil solution. Therefore, zeolites may function as slow-release nutrient carriers, depending on their mineralogical and chemical composition.

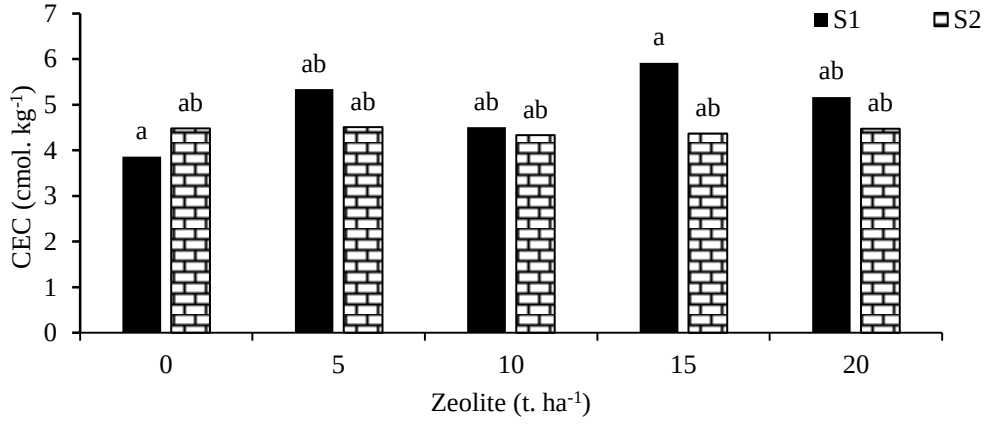



**Fig. 1**. *Influence of zeolite on soil CEC. Bars sharing different letters differ significantly at p < 0.05. S1 = Season 1, S2 = Season 2.*

**Effect of zeolite on exchangeable potassium ($K^+$ )**

Exchangeable $K^+$ is an important indicator of potassium availability because it represents the fraction of potassium held on the exchange sites that can be readily released for plant uptake (Delgado et al., 2024). In this study, exchangeable $K^+$ increased with zeolite application rate (Fig. 2). The highest values were observed at 15 t. $ha^{-1}$ (0.57 cmol. $kg^{-1}$) in S1 and 20 t. $ha^{-1}$ (0.80 cmol. $kg^{-1}$) in S2, while the control recorded the lowest values in both seasons. The zeolite contained 1.70% $K_2O$ (Table 2). This K may have added to the exchangeable pool alongside the K applied as KCl fertiliser. This increase reflects the additional exchange sites zeolite provides, which retain $K^+$ against leaching (Wangi et al., 2023). The pattern corresponds with the increase in CEC observed with zeolite application in Fig. 1, which provides greater capacity for retaining exchangeable $K^+$.

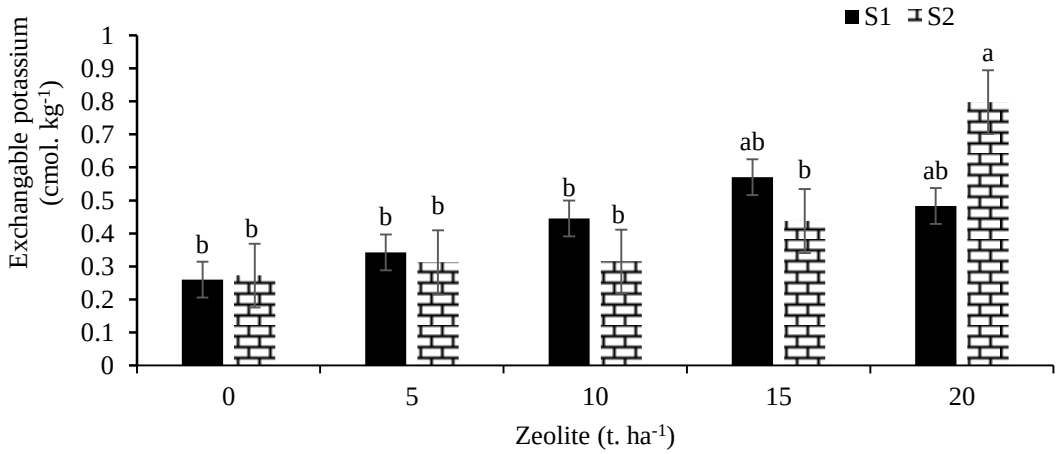



**Fig. 2**. *Influence of zeolite on soil Exchangeable potassium. Bars sharing different letters differ significantly at p < 0.05. S1 = Season 1, S2 = Season 2.*

**Effect of zeolite on exchangeable sodium ($Na^+$)**

Exchangeable $Na^+$ is an important indicator of soil chemical status because it contributes to the pool of exchangeable cations and can influence soil chemical properties when present at elevated concentrations (Ćirić et al., 2023). In Fig. 3 $Na^+$, was lowest in the control in both seasons, 0.32 cmol. $kg^{-1}$ in S1 and 0.30 cmol. $kg^{-1}$ in S2. The highest value, 0.48 cmol. $kg^{-1}$, occurred at 10 t. $ha^{-1}$ in S1. Zeolite exchange sites can retain $Na^+$ along with other exchangeable cations, resulting in higher exchangeable $Na^+$ concentrations than the control following zeolite application (Nath et al., 2025). The zeolite contained 2.30%. $Na_2O$ (Table 2). This was the largest share among the four basic cation oxides ($Na_2O$, $K_2O$, MgO, and CaO). The higher $Na^+$ under zeolite agrees with this composition. The inconsistent increase in exchangeable $Na^+$ at higher zeolite rates may indicate competition among $Na^+$, $K^+$, $Mg^{2+}$ and $Ca^{2+}$ for available exchange sites, with the relative abundance and selectivity of these cations influencing their retention in the soil (Nam et al., 2026).

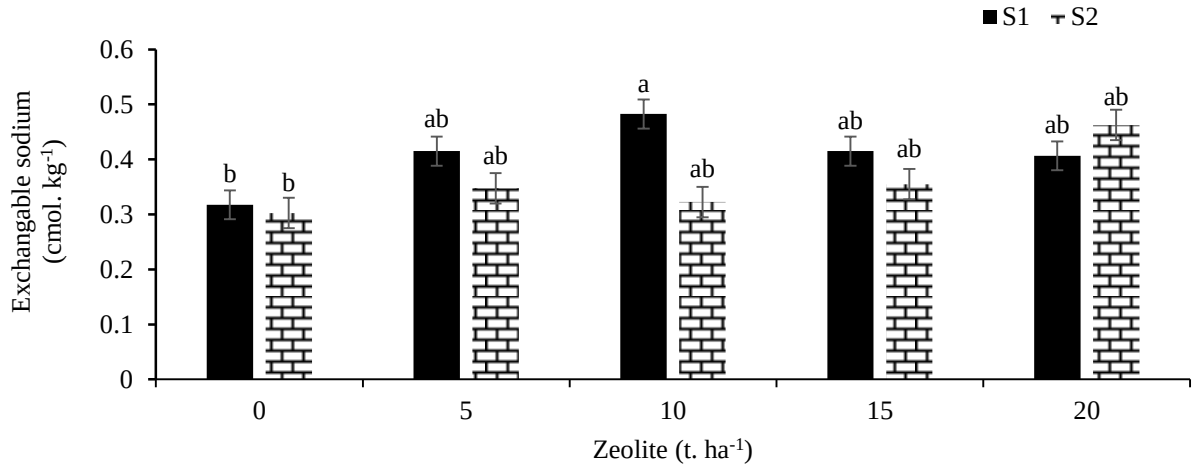



**Fig. 3**. *Influence of zeolite on soil Exchangeable sodium. Bars sharing different letters differ significantly at p < 0.05. S1 = Season 1, S2 = Season 2.*

**Effect of zeolite on exchangeable magnesium ($Mg^{2+}$)**

Exchangeable $Mg^{2+}$ is an important measure of magnesium availability because magnesium is an essential plant nutrient involved in chlorophyll formation and photosynthesis (Ahmed et al., 2023). In this study, exchangeable $Mg^{2+}$ ranged from 1.01 cmol. $kg^{-1}$ in the control in S1 to 1.40 cmol. $kg^{-1}$ at 20 t $ha^{-1}$ in S2 (Fig. 4). However, no significant differences were observed among the zeolite treatments or between seasons. The zeolite contained 1.30%. MgO, which was lower than its $Na_2O$ and $K_2O$ contents (Table 2). The absence of a $Mg^{2+}$ response agrees with this composition. The absence of a significant effect may be related to the relatively stable availability of $Mg^{2+}$ in the soil, while the negatively charged exchange sites associated with zeolite may contribute to $Mg^{2+}$ retention in the soil (Jin et al., 2025). Thus, zeolite application did not significantly affect exchangeable $Mg^{2+}$ under the conditions of this study.

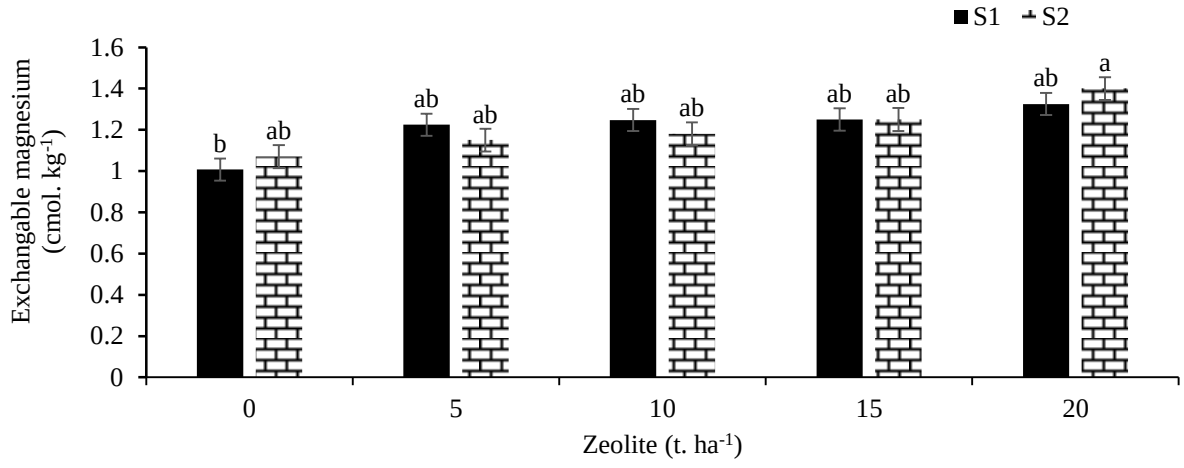



**Fig. 4**. *Influence of zeolite on soil Exchangeable magnesium. Bars sharing different letters differ significantly at p < 0.05. S1 = Season 1, S2 = Season 2*

**Effect of zeolite on exchangeable calcium ($Ca^{2+}$)**

Exchangeable $Ca^{2+}$ is an important indicator of calcium availability because calcium is an essential plant nutrient that contributes to cell wall development, membrane stability, and plant growth (Wdowiak et al., 2024). Fig. 5 shows no significant difference in exchangeable $Ca^{2+}$ across treatments or seasons. The zeolite contained 1.20% CaO (Table 2). This was the lowest of the four basic cation oxides. The absence of a $Ca^{2+}$ response agrees with this composition. This suggests that zeolite application did not alter the $Ca^{2+}$ of the study, possibly because the existing soil $Ca^{2+}$ levels were sufficient to maintain $Ca^{2+}$ availability across treatments.

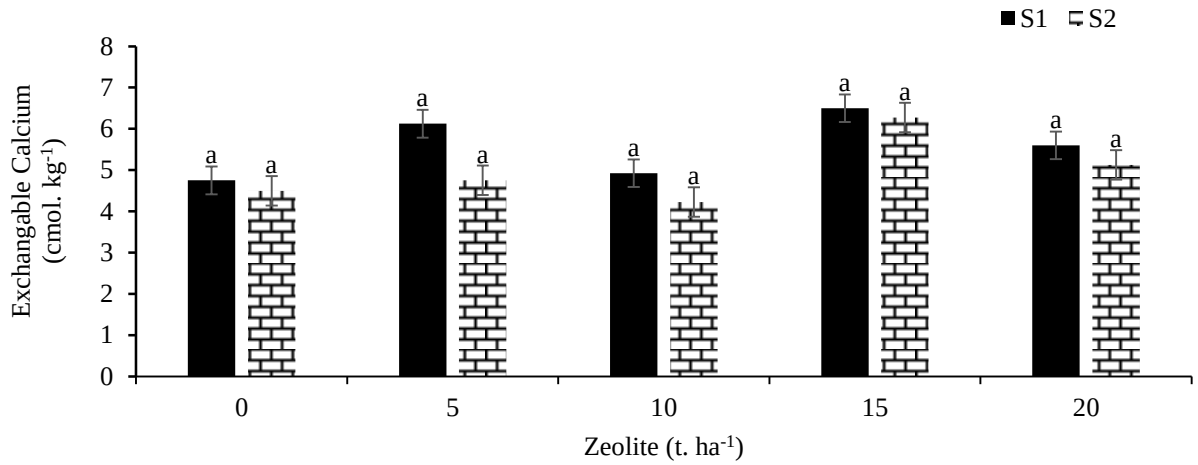



**Fig. 5**. *Influence of zeolite on soil Exchangeable calcium. Bars sharing different letters differ significantly at p < 0.05. S1 = Season 1, S2 = Season 2*

**Effect of zeolite on plant-available phosphorus**

Plant-available phosphorus (P) is an important indicator of phosphorus availability in soil, as it is an essential macronutrient involved in energy transfer, root development, and plant growth (Anjum et al., 2024). Plant-available P did not increase consistently with zeolite rate (Fig. 6). The highest numerical values occurred at 15 t. $ha^{-1}$ in both seasons, 116.8 mg. $kg^{-1}$ in S1 and 149.95 mg. $kg^{-1}$ in S2, while the lowest occurred at 10 t. $ha^{-1}$, 41.75 and 52.38 mg. $kg^{-1}$, with 15 t. $ha^{-1}$ only significantly higher than the 10 t. $ha^{-1}$ treatment while having numerical advantage over the remaining treatments.

In S2, no significant differences were observed among the zeolite treatments, although the highest value was recorded at 15 t. $ha^{-1}$. However, this value did not differ significantly from that of the control. Baseline available P was 82.2 mg. $kg^{-1}$ (Bray II; Table 1). The lowest values at 10 t. $ha^{-1}$ fell below this baseline in both seasons. The highest values, at 15 t. $ha^{-1}$, exceeded the baseline value. Zeolite's cation exchange capacity does not directly retain phosphate because phosphate is an anion. Therefore, its effect on P availability is likely to be indirect (Stocker and Ellersdorfer, 2022). The rise at 15 t. $ha^{-1}$ followed by a decline at 20 t. $ha^{-1}$ indicates a secondary process, such as pH-driven changes in phosphate solubility, rather than a direct effect of zeolite rate.

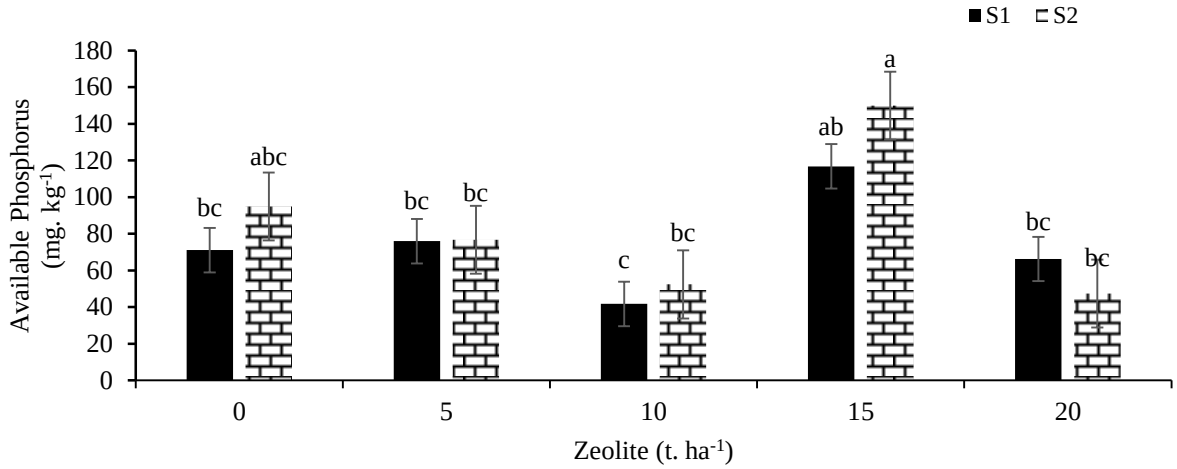



**Fig. 6**. *Influence of zeolite on soil available phosphorus. Bars sharing different letters differ significantly at p < 0.05. S1 = Season 1, S2 = Season 2*

**Effect of zeolite on plant-available potassium (K)**

Plant-available potassium is an essential macronutrient involved in water regulation, enzyme activation, and plant growth (Rodríguez-Iznaga et al., 2026). In general, plant-available K increased numerically with increase in zeolite application in both seasons, with the exception of 20 t. $ha^{-1}$ in S2 which was significantly higher in available K compared to the other treatments (Fig.7). The control values in both seasons were below the 178 mg. $kg^{-1}$ baseline available K (Table 1). However, at the highest zeolite application rates of 15 t. $ha^{-1}$, 20 t. $ha^{-1}$ in S1 and 20 t. $ha^{-1}$ were above it. This increase corresponds with the increase in exchangeable $K^+$ at the same rates, since exchangeable $K^+$ forms the readily plant-available fraction of soil K (Mizutani et al., 2024). The $K_2O$ content of the zeolite (1.70%; Table 2) may also have contributed.

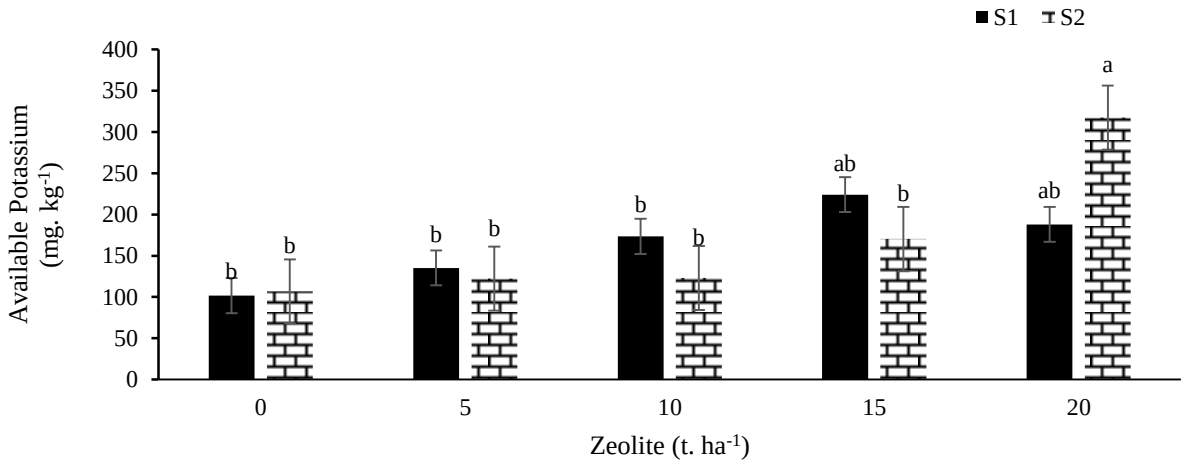



**Fig. 7**. *Influence of zeolite on soil plant-available potassium. Bars sharing different letters differ significantly at p < 0.05. S1 = Season 1, S2 = Season 2*

**Soil pH response to zeolite application**

Soil pH is an important soil chemical characteristic. It controls nutrient availability, microbial activity, and plant growth and yield (Singh and Singh, 2025). Vegetables generally grow best at a pH ranging from 5.5 to 6.5. The baseline pH (KCl) was $6._3$ (Table 1), which is within this range. Soil pH varied significantly among treatments (Fig. 8).

It did not increase consistently with zeolite rate. The highest pH in S1 was 6.65 at 10 t. $ha^{-1}$. The highest pH in S2 was 6.37 at 15 t. $ha^{-1}$. The lowest pH was 6.15 at 15 t. $ha^{-1}$ in S1 and 5.93 at 10 t. $ha^{-1}$ in S2. Zeolite carries exchangeable basic cations, and these can displace $H^+$ from the soil exchange complex and reduce soil acidity (Zhang et al., 2023). The higher exchangeable $K^+$ and $Na^+$ under zeolite are consistent with this mechanism. The variation between rates and seasons indicates that other factors also influenced pH.

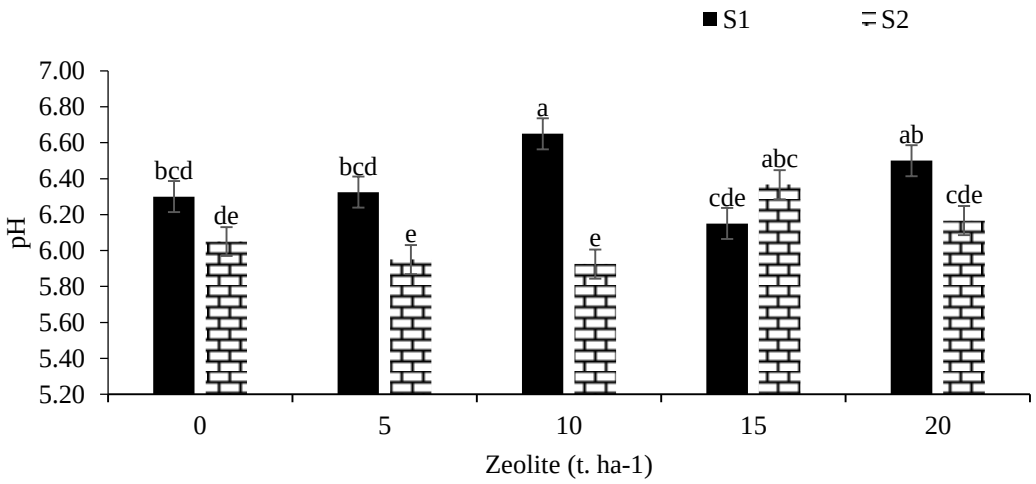



**Fig. 8**. *Effect of zeolite on soil pH. Bars sharing different letters differ significantly at $p < 0.05$. S1 = Season 1, S2 = Season 2.*

**Influence of zeolite on soil organic matter and carbon**

Soil organic matter (SOM) and soil organic carbon (SOC) are closely linked soil chemical properties (Chen et al., 2023). SOM is the total body of organic material in the soil, while SOC is the C component of that body. In this study, both SOM (Fig. 9) and SOC (Fig. 10) did not show significant differences across treatment and season, but there was a tendency amongst both parameters to have slightly higher C.

The slight increase in SOM and SOC with higher treatments may reflect minor accumulation of organic residues, though the differences were not statistically significant, suggesting limited short-term impact of the amendments on soil carbon (Sindesi et al., 2022).

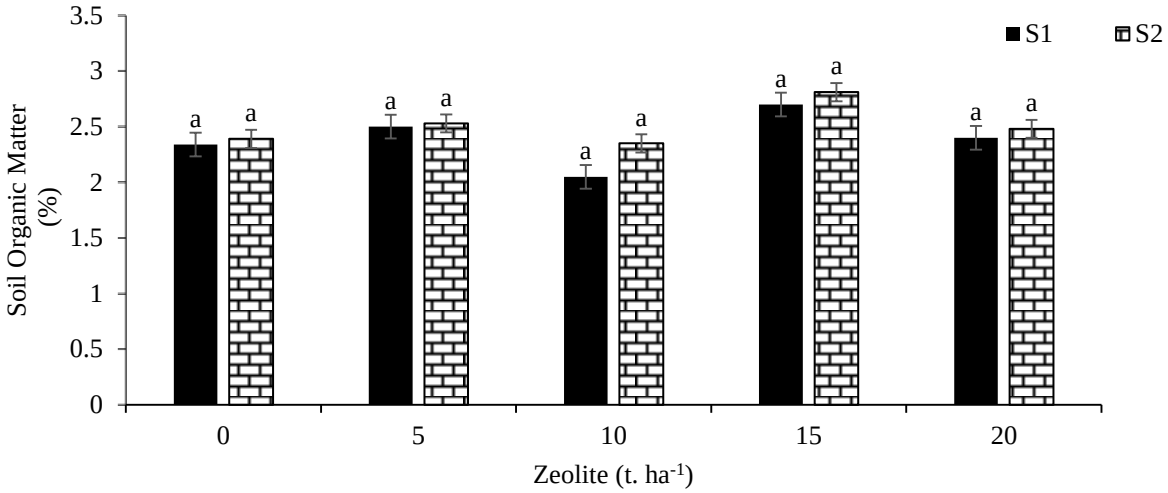



**Fig. 9.** *SOM (%) responses to zeolite application. Bars sharing different letters differ significantly at p < 0.05.S1 = Season 1, S2 = Season 2*

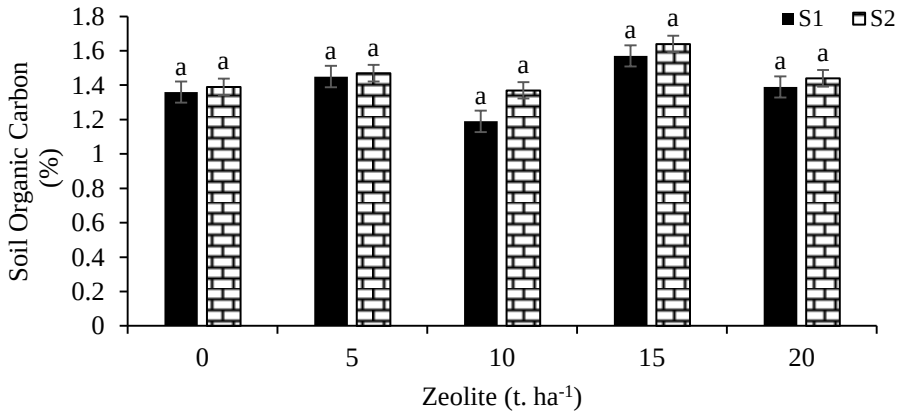



**Fig. 10**. *Effect of zeolite on SOC (%). Bars sharing different letters differ significantly at p < 0.05. S1 = Season 1, S2 = Season 2.*

**Effect of zeolite on Mineral N**

Nitrogen is available to plants in inorganic forms (nitrate and ammonium) and organic forms urea, free amino acids, and short peptides (Kumari et al., 2022). Urea must first hydrolyse to ammonium before crops can use it. In this study, total plant-available nitrogen was calculated using the $NO_3^-$ and $NH_4^+$, in accordance with the method described by Sindesi et al. (2024). Mineral N did not increase consistently with zeolite rate (Fig. 11). Values were higher in S2 than in S1. The control (0 t. ha$^{-1}$) recorded the highest value in S2 (44.2 mg. kg$^{-1}$), while 10 t. ha$^{-1}$ showed the lowest Mineral N content in both seasons. Baseline $NO_3^-$ and $NH_4^+$ were 14.4 and 6.2 mg. kg$^{-1}$, giving 20.6 mg. kg$^{-1}$ of Mineral N (Table 1). The S2 control value was more than twice this baseline. Urea applied at planting would have contributed to this rise. The lower Mineral N concentrations observed in the zeolite-amended treatments may be related to the retention of $NH_4^+$ through ion exchange within the zeolite structure (Nath et al., 2025). This retained nitrogen may be released gradually into the soil

solution, suggesting that zeolite may function as a slow-release nutrient carrier (Soltys et al., 2020). The results indicate that nitrogen availability differed among zeolite application rates and did not consistently increase with increasing zeolite application rate.

The higher Mineral N content recorded in the control treatment in S2 may indicate greater availability of readily measurable mineral N, whereas the zeolite-amended treatments may have temporarily retained a greater proportion of $NH_4^+$ (Rosinger et al., 2026). The variation across treatments, with no consistent increase at higher rates, indicates that zeolite influences N retention and transformation differently depending on soil conditions and season (Szatanik-Kloc et al., 2021; Ahmad et al., 2025).

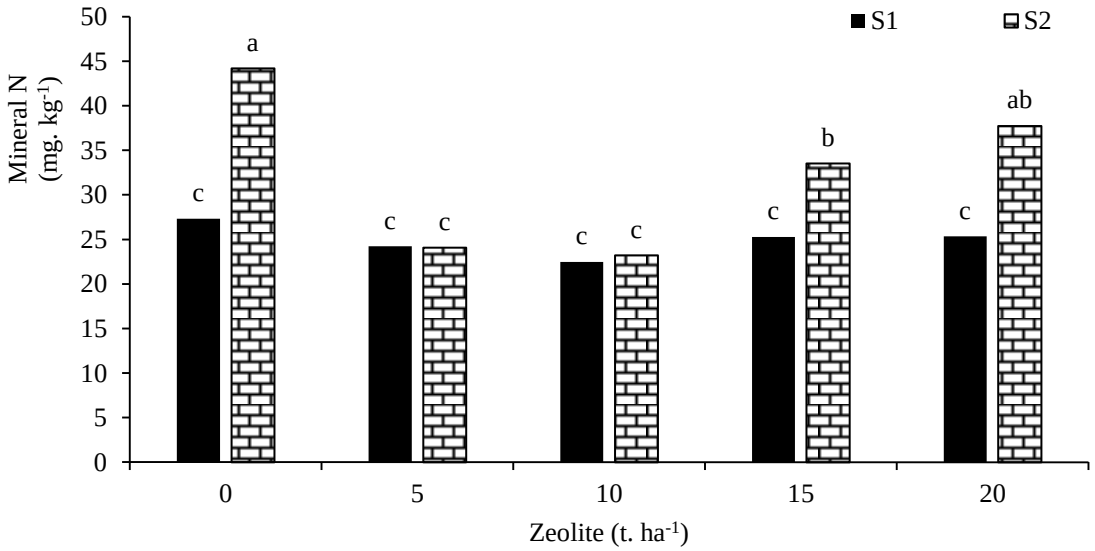



**Fig. 11.** *Effect of zeolite on Mineral N. Bars sharing different letters differ significantly at p < 0.05. S1 = Season 1, S2 = Season 2.*

**Effect of zeolite on dry yield**

Dry yield is an important indicator of biomass production and crop productivity (Kavvadias et al., 2023). In S1, dry yield increased from 14.7 t. ha$^{-1}$ in the control to 20.5 t. ha$^{-1}$ at 20 t. ha$^{-1}$ zeolite (Fig 12). In S2, yields were higher, ranging from approximately 24.6 t. ha$^{-1}$ at 10 t. ha$^{-1}$ to 29.0 t. ha$^{-1}$ at 20 t. ha$^{-1}$. The highest dry yield was recorded at 20 t. ha$^{-1}$ in both seasons, although it was not significantly different from the other treatments. Baseline available P and K were 82.2 and 178 mg. kg$^{-1}$ (Table 1).

Fertiliser P and K were also applied at planting. Nutrient supply in the control may therefore have been adequate. This could limit any yield response to zeolite. The higher yields at the greater zeolite rates coincided with the higher CEC and exchangeable $K^+$ (Figs. 1 and 2), which suggests improved nutrient retention in the root zone, although the yield differences were not significant (Mumpton, 1999; Mondal et al., 2021; Legese et al., 2024).

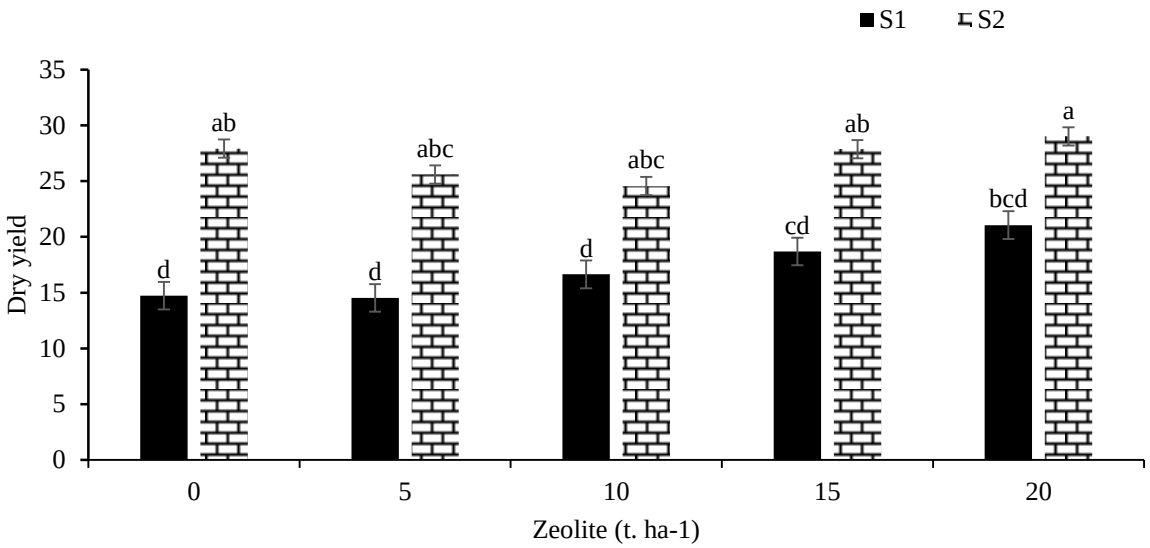



**Fig. 12** *Effect of zeolite on Dry yield of lettuce. Bars sharing different letters differ significantly at p < 0.05. S1 = Season 1, S2 = Season 2.*

**Conclusion**

This research demonstrates that zeolite application at moderate rates of 10–15 t.ha$^{-1}$ significantly increased soil cation exchange capacity (CEC) in South African lettuce production. The soil's CEC reached a maximum of 5.92 cmol. kg$^{-1}$ at the 15 t. ha$^{-1}$ rate during the first season, a significant increase over the 3.86 cmol. kg$^{-1}$ observed in the control treatment. This enhancement may be attributed to the mineral's high surface area and negatively charged structure, which creates additional sites for retaining cations such as $K^+$, $Ca^{2+}$ , and $NH_4^+$. Mineral N did not increase consistently with the zeolite rate. In S2, the control recorded the highest value (44.2 mg. kg$^{-1}$). The lower values in the zeolite treatments may relate to $NH_4^+$ retention through ion exchange, but this was not measured directly. Soil pH was within the range considered optimal for vegetables (5.5 to 6.5). The highest values were recorded at 10 t. ha$^{-1}$ in S1 and 20 t. ha$^{-1}$ in S2.

Treatment effects on SOM and SOC were not significant. Lettuce dry yield varied numerically among zeolite application rates; however, no statistically significant treatment effect was observed. The increased CEC observed with zeolite application indicates it's potential to improve nutrient retention when used together with, rather than as a replacement for, inorganic fertiliser. The higher CEC observed following zeolite application suggests an increased capacity for nutrient retention (Mondal et al., 2021). However, potential reductions in nutrient leaching and fertiliser requirements remain untested, as these parameters were not directly measured in the present study.

Further research should investigate zeolite in combination with reduced inorganic fertiliser rates to determine whether fertiliser inputs can be lowered without compromising lettuce growth and yield. Multi-season and multi-location trials are recommended to establish the consistency and long-term effects of zeolite application under different soil and climatic conditions. Long-term studies should also assess changes in soil health, nutrient cycling and soil structural properties. A limitation of the present study was that soil particle size

distribution, bulk density, water-holding capacity and soil moisture were not measured, limiting the interpretation of the effects of zeolite on soil physical and water-related properties. Economic evaluations are recommended to determine the feasibility and cost-effectiveness of integrating zeolite with inorganic fertiliser in commercial lettuce production.

**Acknowledgments**

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**References**

Ahmad, A., Ijaz, S.S., Zhao, F., Rafa, H.U. and Farid, G. 2025. The effect of zeolitic fertilizer on nitrogen retention in soil and its availability to plants. *Nitrogen*, *6*(2), 46.

Ahmed, N., Zhang, B., Bozdar, B., Chachar, S., Rai, M., Li, J., Li, Y., Hayat, F., Chachar, Z. and Tu, P. 2023. The power of magnesium: unlocking the potential for increased yield, quality, and stress tolerance of horticultural crops. *Frontiers in Plant Science*, *14*, p.1285512.

Anjum, N.A., Masood, A., Umar, S. and Khan, N.A. 2024. Introductory chapter: Phosphorus in soils and plants. In *Phosphorus in soils and plants*. IntechOpen.

Antoniadis, V., Damalidis, K. and Dimirkou, A. 2012. Availability of Cu and Zn in an acidic sludge-amended soil as affected by zeolite application and liming. Journal of Soils and Sediments, 12(3), 396-401.

Blanco, H. and Lal, R. 2023. Soil fertility management. In *Soil conservation and management* ( 363-390). Cham: Springer Nature Switzerland.

Chen, X., Xu, Y., Sun, R., Ye, X., Ma, C., Mao, J., Zhang, C., Gao, H. and Zhang, W. 2023. Soil microbial communities under wheat and maize straw incorporation are closely associated with soil organic carbon fractions and chemical structure. *Applied Soil Ecology*, *182*, 104724.

Ćirić, V., Prekop, N., Šeremešić, S., Vojnov, B., Pejić, B., Radovanović, D. and Marinković, D. 2023. The implication of cation exchange capacity (CEC) assessment for soil quality management and improvement. *Agriculture & Forestry/Poljoprivreda i šumarstv*, *69*(4), p.113.

Delgado, A., Quemada, M., Mateos, L. and Villalobos, F.J. 2024. Fertilization with phosphorus, potassium, and other nutrients. In *Principles of agronomy for sustainable agriculture* (pp. 415-437). Cham: Springer International Publishing.

Dimkpa, C., Adzawla, W., Pandey, R., Atakora, W.K., Kouame, A.K., Jemo, M. and Bindraban, P.S. 2023. Fertilizers for food and nutrition security in sub-Saharan Africa: an overview of soil health implications. *Frontiers in Soil Science*, *3*, 1123931.

Farhan, M., Sathish, M., Kiran, R., Mushtaq, A., Baazeem, A., Hasnain, A., Hakim, F., Hasan Naqvi, S.A., Mubeen, M., Iftikhar, Y. and Abbas, A. 2024. Plant Nitrogen Metabolism: Balancing Resilience to Nutritional Stress and Abiotic Challenges. *Phyton* (0031-9457), 93(3).

Jin, Y., Wu, H., Huo, S., Chen, S., Shen, L., Di, H., Du, L. and Li, P. 2025. $Mg^{2+}$ - modified corncob biochar and natural zeolite significantly enhanced simultaneous N and P recovery from livestock wastewater. *Plos one*, *20*(8), p.e0331575.

Kavvadias, V., Ioannou, Z., Vavoulidou, E. and 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.

Khan, M.R., Tarafder, M.A. and Priti, M.S., 2024. Potential use of zeolites in agriculture: A review. *SAARC Journal of Agriculture*, *22*(1), 17-30.

Lal, R. 2012. Climate change and soil degradation mitigation by sustainable management of soils and other natural resources. *Agricultural Research*, 1, 199-212.

Legese, W., Taddesse, A.M., Kibret, K. and Wogi, L. 2024. Effects of natural and modified zeolite based composite fertilizers on slow release and nutrient use efficiency. *Heliyon*, *10*(3).

Mirzaei Aminiyan, M., Safari Sinegani, A.A. and Sheklabadi, M. 2015. Aggregation stability and organic carbon fraction in a soil amended with some plant residues, nanozeolite, and natural zeolite. International Journal of Recycling of Organic Waste in Agriculture, 4(1), 11-22.

Mizutani, Y., Kubotera, H., Fujii, T., Maeda, T., Watanabe, M. and Hiradate, S. 2024. Recharge of exchangeable K from non-exchangeable fractions as affected by exchangeable K and K acquisition by rice in Japanese paddy soils. *Soil Science and Plant Nutrition*, *70*(4), pp.295-305.

Mondal, M., Biswas, B., Garai, S., Sarkar, S., Banerjee, H., Brahmachari, K., Bandyopadhyay, P.K., Maitra, S., Brestic, M., Skalicky, M. and Ondrisik, P. 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*, *96*(7), 3463-3470.

Mutengwa, C.S., Mnkeni, P. and Kondwakwenda, A. 2023. Climate-smart agriculture and food security in Southern Africa: A review of the vulnerability of smallholder agriculture and food security to climate change. *Sustainability*, *15*(4), 2882.

Nam, T., Yasumura, S. and Ogura, M. 2026. Comparative study on Cs+ ion-exchange behavior in zeolites with different framework structures and compositional characteristics. *Microporous and Mesoporous Materials*, *400*, p.113898.

Nath, S., Lim, H.S., Kim, H.S. and Lim, W.T. 2025. Ion distribution and structural modification in zeolite LTA via Na+ and Mn2+ ion exchange. *Journal of Porous Materials*, *32*(5), pp.1843-1853.

Non-Affiliated Soil Analysis Work Committee, 1990. Handbook of standard soil testing methods for advisory purposes. *Soil Science Society of South Africa, Pretoria*, *160* (2020), p.10.

Rodríguez-Iznaga, I., Shelyapina, M.G. and Petranovskii, V. 2026. Ion Exchange as a Method of Conditioning Natural Zeolites to Potentiate Their Use. In *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications* (pp. 1-33). Cham: Springer Nature Switzerland.

Rosinger, C., Wieshammer, G., Ferretti, G. and Kaul, H.P. 2026. Contrasting Effects of Uncharged and Nitrogen-Charged Chabazite-Zeolite Amendment on Physiology, Growth and Nutrient Uptake of Barley (Hordeum vulgare) Under Drought. *Agronomy*, *16*(4), p.417.

Sindesi, O.A., Lewu, M.N., Ncube, B., Meyer, A., Mulidzi, A.R. and Lewu, F.B. 2024. Effect of zeolite application on soil enzyme activity of potted sandy soil cultivated with Swiss chard and cabbage. *Eurasian Journal of Soil Science*, *13*(4), pp.284-29.

Sindesi, O.A., Lewu, M.N., Ncube, B., Mulidzi, A. and Lewu, F.B. 2022. Residual effect of zeolite on soil exchangeable cations and cation exchange capacity in sandy soil cultivated with Swiss Chard.

Sindesi, O.A., Mashece, W., Lupiwana, M. and Seti, T.M. 2026. Role of Zeolite Soil Amendments in Crop Production: Enhancing Soil Health and Food Security in a Changing Climate. In *Climate Change, Food Security, and Land Management: Strategies for a Sustainable Future* (pp. 1-23). Cham: Springer Nature Switzerland.

Singh, K. and Singh, S.K. 2025. Influence of Soil pH on Nutrient Availability and Plant Growth. *Journal of Science Innovations and Nature of Earth*, *5*(1), 105-108.

Soltys, L., Myronyuk, I., Tatarchuk, T. and Tsinurchyn, V. 2020. Zeolite-based composites as slow release fertilizers. *Physics and Chemistry of Solid State*, *21*(1), pp.89-104.

Kumari, R., Bhatnagar, S. and Kalra, C., 2022. Nitrogen assimilation in plants. In *advances in plant nitrogen metabolism* (pp. 38-54). CRC Press.

Stocker, K. and Ellersdorfer, M. 2022. Phosphate fixation and P mineralogy on natural and Ca-Modified zeolites during simultaneous nutrient removal. *Water, Air, & Soil Pollution*, *233*(2), p.41.

Szatanik-Kloc, A., Szerement, J., Adamczuk, A. and Jozefaciuk, G. 2021. Effect of low zeolite doses on plants and soil physicochemical properties. *Materials*, 14(10), 2617.

Wangi, G.M., Olupot, P.W., Byaruhanga, J. and Kulabako, R. 2023. Characterization of Natural Zeolite and Determination of its Ion-exchange Potential for Selected Metal Ions in Water: GM Wangi et al. *Environmental Processes*, *10*(4), p.53.

Wdowiak, A., Podgórska, A. and Szal, B. 2024. Calcium in plants: an important element of cell physiology and structure, signaling, and stress responses. *Acta Physiologiae Plantarum*, *46*(12), p.108.

Zhang, S., Zhu, Q., de Vries, W., Ros, G.H., Chen, X., Muneer, M.A., Zhang, F. and Wu, L. 2023. Effects of soil amendments on soil acidity and crop yields in acidic soils: A world-wide meta-analysis. *Journal of Environmental Management*, *345*, 118531.