JEE Journal of Ecological Engineering

*Journal of Ecological Engineering*, 2025, 26(11), 369–379
https://doi.org/10.12911/22998993/207998
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.06.19
Accepted: 2025.08.01
Published: 2025.08.15

# Investigating the Impact of nano-calcium loaded zeolite on the germination and growth of corn (*Zea mays* L.)

Liqaa I. Saeed[1*], Nahla Salim Hammok[2]

[1] College of Petroleum and Mining Engineering, Department of Mining Engineering, University of Mosul, Mosul, 41002, Iraq
[2] Environmental Researches Center, University of Mosul, Iraq
* Corresponding author's e-mail: l.idrees.saeed@uomosul.edu.iq

## ABSTRACT

This research examines the impacts of nano-calcium and zeolite treatments on germination and growth development in *Zea mays*. There were three experimental setups used, including germination in petri dishes, soil-based growth in germination trays, and combined application of nano-calcium as a load in zeolite within the soil. The first experiment reported a sharp decline in germination rate with increasing nano-calcium concentration, with maximum germination rate reported at 0.5% concentration of nano-calcium (96%). There was also a sharp decrease in root length at increased nano-calcium concentrations. However, there were no effects on other growth parameters. The second experiment reported the positive role played by zeolite application, with 2% concentration of zeolite significantly enhancing shoot growth compared to the control. There were no effects on other growth parameters. The third experiment illustrated that combined nano-calcium and zeolite application exerted significant effects on germination rates and biomass in plants with improved fresh and dry weight at moderate concentration levels of zeolite and nano-calcium. These results indicate that moderate levels of nano-calcium and zeolite have the potential to improve plant growth through better water holding and availability of nutrients without causing toxicity.

**Keywords:** calcium nanomaterials, zeolite, *Zea mays*, germination, growth parameters, root length, shoot height, soil amendments, plant growth promotion.

## INTRODUCTION

Application of advanced fertilizer systems and soil amendments based on nanotechnology has gained prominence in recent years as a result of sustainable crop production requirements and improved nutrient management. Among these soil amendments, zeolites have been researched intensively as means to enhance physical soil structure, regain nutrient retention, and promote plants' growth performance (1). Zeolites are crystalline minerals based on aluminosilicates with high cation exchange capacity (CEC) and porosity in order to provide controlled release of water and nutrients (2–4). Introduction of zeolites to agricultural land has been reported to have a variety of positive impacts, including improved aeration of soil, better availability of moisture (5), and increased efficiency in fertilizer use. Various studies have demonstrated zeolite-based amendments to improve crop yield, particularly in drought-stricken or nutrient-deficient areas of soil by sustaining slow-release nutrition with decreased leaching loss (6, 7). For example, zeolite application on maize has been reported to improve nitrogen utilization efficiency, aiding root growth promotion and increased overall vigor (8, 9). Besides this, studies have also demonstrated zeolites to reduce soil salinity stress (10–12) and become an attractive choice to improve productivity in barren lands (2). In spite of all these advantages, there remain several limitations, including soil compaction in fine-textured zones and poor nutrient accessibility in some areas by strong ion-binding reaction. Apart from this, high costs of production and source limitations in some cases may oppose large-scale utilization by its adoption (2). Parallel with zeolite-based amendments, calcium is also a vital macronutrient playing a critical role in above- and below-ground development of growth in plants, affecting cell wall stability, membrane function, signal transduction, and enzyme activity. Calcium deficiency in plants is characterized by reduced root elongation, lower resistance to stress, and reduced frequency of germination, further necessitating its supplementation needs (13, 14). The application constraints with convention-based materials such as calcium carbonate, gypsum, and calcium nitrate are low solubility, high leaching susceptibility, as well as poor efficiency in nutrient absorption. In order to buffer these constraints, nano-calciuim fertilizers have come forward as means to improve forms in a bioavailable state as well as efficiency in absorption. Due to their nano-scaled dimensions, nano-calcium-based fertilizers possess an increased degree of reactivity, better root and leaf penetration, and better translocation through plant tissues. According to studies, nano-calcium applications have been reported to increase chlorophyll production, shoot elongation, and germination of seeds, particularly under abiotic stress conditions (15–17). Moreover, nano-calcium has also been reported to enhance drought tolerance and salt tolerance in maize and wheat plants with a greater physiological response and stability in yield (18). However, its fate in the environment, bioaccumulation, and potential toxicity have not been widely researched despite its potential benefits. Excessive application of nano-calcium has been reported by some studies as having the potential to disrupt nutrient balance, thereby inducing unwanted physiological responses in plants or soil microbiota, with long-term effects on soil health (17). While zeolite and nano-calcium have both independently been reported to have positive effects on plant growth, an integrated application is relatively a new area. The nano-calcium impregnation within zeolite is a novel way of enhancing availability with simultaneous utilization of zeolite's water reserve and nutrient management functions. Such an application can result in controlled release as calcium ions, with defined delivery at sites in plants' roots, with a more stable nutrient supply at early growth stages when calcium is most vital. The hope is to have nano-calcium-loaded zeolite with greater rates for improved germination, increased root elongation rates, and greater biomass production overall than with normal fertilization techniques. There is also a possibility with over-absorption of calcium by zeolite's framework making its bioavailability less immediate and, also, maintaining precise formulation to prevent imbalance in nutrients. There also needs to be consideration for large-scale zeolite synthesis as well as nano-calcium impregnating on industrial scales before integration into agriculture on large scales is acceptable. Based on these considerations, this research will examine how nano-calcium-impregnated synthetic zeolite impacts germination and development in maize (*Zea mays L.*) seeds. The goals are to quantify germination rate, root-shoot biomass production, chlorophyll concentration, and vigor in plants, comparing its performance against normal fertilization with normal fertilizers. This research will shed more lights on zeolite-nano-calcium synergy potential for more efficient, sustainable, and targeted fertilization technologies for agriculture.

## MATERIALS AND METHODS

Three experiments were carried out in the Environment Research Center's Research Laboratory at the University of Mosul in accordance with the following procedures:

### Collecting and characterising soils

The soil was collected from the University of Mosul's silty bios units. Standard procedures were followed in the analysis of its physical and chemical characteristics. Electric conductivity (EC) was measured at 0.3 dS/m, and the pH of the soil was 7.2, indicating neutral conditions. Gravimetric soil moisture measurement involves weighing wet soil samples, drying them in an oven, and weighing them again. Calculated moisture using weight differences. The lab temperature ranged from 25 to 35 °C. Under these conditions, soil moisture varied 25–35% daily.

### Preparation of nano-calcium concentrations

The concentrations of nano-calcium used in this study were 0.5, 1, and 2 mg/mL. These concentrations were chosen based on the application rates utilised by Hussein and Ibraheem (2023), who applied comparable concentrations to potato cultivars through foliar treatments. (19), who applied comparable concentrations to potato cultivars through foliar treatments. In the first experiment, the same concentrations were also tested for their impact on maize seed viability by evaluating their effect on germination in Petri dishes. Five nano-calcium concentrations were synthesised as follows (Table 1):

## Methodology for zeolite application

Based on ranges documented in earlier research, zeolite was added at rates of 2 and 5 g per 2 kg of soil (or 1 and 2.5 g/kg) (20, 21). To analyze the impacts of zeolite on soil characteristics and crop growth, two doses were used to prepare the applications. For the first treatment, 2 grams of zeolite were added to the same amount of air-dried soil. For the second treatment, the same amount of soil was used but with the addition of 5 grams of zeolite. Following the addition of soil amendment, the resulting mixtures were carefully placed into seedling trays consisting of 77 evenly spaced perforated cells (7 rows by 11 columns). A control group involving untreated soil irrigated only with distilled water was also set to create a basis of comparison. For each of the treatments, in each replicate, the seeds were planted at a rate of 10 in such a manner that uniform distribution was ensured. Three replications for each treatment were ensured to assure statistical significance.

## Planting seed

*Experiment 1 – planting in Petri dishes*

Visually robust and uniformly sized yellow-colored seeds were selected on the basis of external morphology. 10 to 15 externally uniform yellow-colored seeds per treatment were placed evenly in sterile Petri dishes, five per concentration. Nano-calcium solution at the rate of 10 milliliters per dish was applied according to specified concentration levels. The dishes were incubated in a controlled condition chamber (Memmert model) at the temperature range of 30 and 35 °C.

**Table 1.** Nano-calcium concentrations (as calcium chloride, $CaCl_2$) provided by Al-Khazra Company, Iran

| Concentration (%) | Nano-calcium (grams per liter) mg/mL |
|---|---|
| Control (0%) | 0 |
| Treatment 1 | 0.5 |
| Treatment 2 | 1 |
| Treatment 3 | 1.5 |
| Treatment 4 | 2 |

Observation and measurement were done at suitable intervals after incubation.

*Experiment 2 – zeolite application in germination trays*

Twenty-five seeds were planted in triplicate in order to analyze the effect of zeolite on germination of the seeds. Among the treatments were 0% (control and irrigated with distilled water), 2%, and 5% concentrations of zeolite. After the seedlings emerged, germination parameters were collected.

*Experiment 3 – applying nano-calcium loaded on zeolite to soil using germination trays*

Various combinations of zeolite loaded with nano-calcium were synthesized by impregnating nano-calcium onto zeolite particles by thorough mixing. The composites were then homogeneously blended into 2 kilograms of air-dried soil to prepare the respective treatments. The following treatment groups were created by repeating this process:
- control: 2 g of zeolite and 2 kg of soil (no nano-calcium),
- 2 kg soil + 2 g zeolite impregnated with 0.5 g nano-calcium,
- 2 kg soil + 2 g zeolite impregnated with 1.0 g nano-calcium,
- 2 kg soil + 2 g zeolite impregnated with 1.5 g nano-calcium,
- 2 kg soil + 2 g zeolite impregnated with 2.0 g nano-calcium.

To evaluate the effects of a second series of treatments on seed germination and early plant development, 5 grammes of zeolite, each previously impregnated with a different proportion of nano-calcium, was mixed with 2 kilogrammes of air-dried soil
- control: 5 g zeolite and 2 kg soil (no nano-calcium),
- 2 kg soil + 5 g zeolite impregnated with 0.5 g nano-calcium,
- 2 kg soil + 5 g zeolite impregnated with 1.0 g nano-calcium,
- 2 kg soil + 5 g zeolite impregnated with 1.5 g nano-calcium,
- 2 kg soil + 5 g zeolite impregnated with 2.0 g nano-calcium.

A total of 30 seeds were planted for each treatment, with 10 seeds per replicate. After the seedlings were apparent, the germination performance was assessed.

### Measurements conducted

In accordance with accepted germination procedures for maize (*Zea mays* L.), germination data concentrated on the crucial 4- to 8-day treatment. Studies indicates that under controlled laboratory conditions, radicle emergence usually starts by day 4 and reaches near-maximum germination by days 7–8(22). The germination percentage was calculated using the formula below after 4 and 8 days of planting:

$$\textit{Germination percentage} = (\textit{Number of germinated seeds} \div \div \textit{Total number of seeds}) \times 100 \quad (1)$$

The shoot length was measured in centimeters. The root length was measured in centimeters. The fresh weight of the seedling was measured in milligrams. The dry weight of the seedling was measured in milligrams. The number of leaves was recorded for each plant.

### Statistical analysis

Statistical analysis followed a factorial design under the CRD approach. Duncan's multiple range Test was utilized to compare the means between the treatments, and different letters were used to indicate significant differences at the defined confidence level (23, 24).

## RESULTS

The research consisted of three separate experiments.

1. The first experiment examined the germination of maize seeds in Petri dishes containing different amounts of nano-calcium.

The germination response of nano-calcium-exposed maize seeds at varied concentrations was the focus of the first experiment. Results showed the effect of nano-calcium to depend on concentration when it came to the rate of germination. At a concentration of 0.5% nano-calcium, after four days, the highest rate of germination (96%) was obtained (Figure 1). Root hair emergence was also stimulated at all the varied concentrations (Figure 2). Statistically significant loss of germination rate was, however, noted at above 0.5% concentration ($p < 0.05$). This inhibitory trend was also evident from the measurements of the root lengths, in which the measurements decreased inversely in proportion to the increases in the concentration of nano-calcium to a minimum of 1.27 cm at the concentration of 2%. Other parameters measured did not exhibit statistically significant differences between treatments (Table 2).

Different letters indicate significant differences at a probability of 0.05, according to Duncan's multiple range test.

2. Experiment 2 – assessment of the impact of zeolite concentration on seed germination in trays filled with soil.

The effect of zeolite amendments on *Zea mays* growth was also measured using soil-based conditions in the second experiment. Statistical analysis revealed a significant improvement in shoot height at the 2% zeolite application, where the seedlings were 12 cm tall, compared to both the control and 5% treatment groups (Figure 3). Other growth parameters that were measured did not exhibit significant treatment differences statistically (Table 3).

Different letters indicate significant differences at a probability of 0.05, according to Duncan's multiple range test.

**Table 2.** Shows how different nano-calcium concentrations affect the germination of maize seeds and early growth characteristics in Petri dishes

| NCa concentration (w/v) (mg/mL) | Germination rate | Root length | Shoot length | Root length | Shoot length | Leaves No. | Fresh weight | Dry weight |
|---|---|---|---|---|---|---|---|---|
| | (After4 day) | | | (After8 day) | | | | |
| 0 | 92ab | 2.62a | 1.79a | 3.46a | 2.84a | 5.00a | 6.10a | 0.20b |
| 0.5 | 96a | 1.48b | 2.03a | 4.20a | 3.94a | 9.20a | 7.64a | 0.20b |
| 1 | 86bc | 1.44b | 1.38a | 2.52a | 2.86a | 7.40a | 6.30a | 0.22a |
| 1.5 | 84bc | 1.39b | 1.43a | 1.97a | 3.03a | 8.40a | 6.71a | 0.21ab |
| 2 | 82c | 1.27b | 1.96a | 1.95a | 3.38a | 9.20a | 6.52a | 0.21ab |

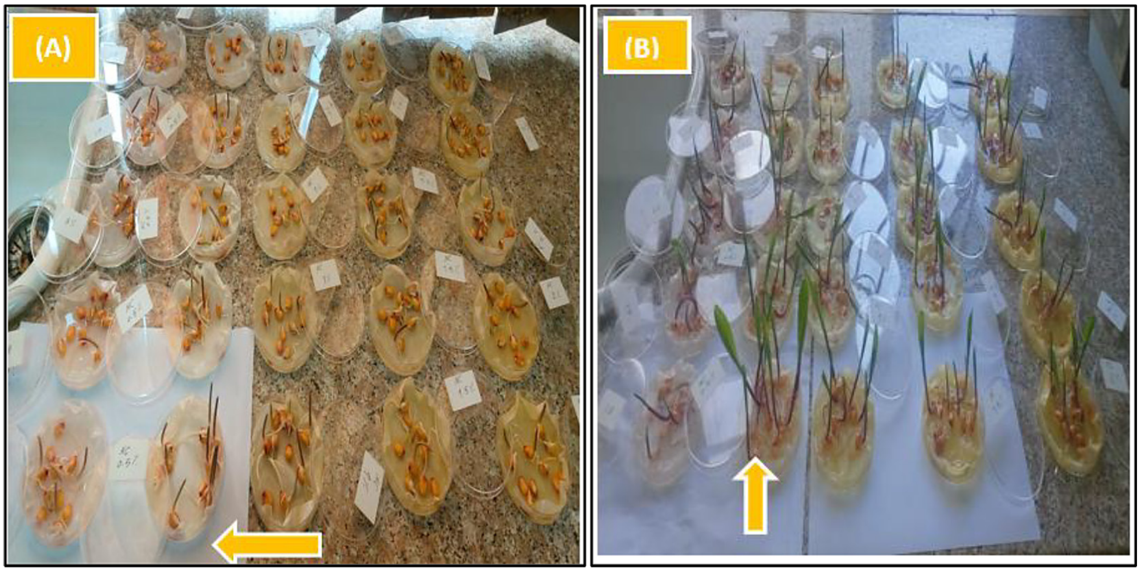


**Figure 1.** Maize seed germination at 0.5% nano-calcium concentration: (A) seedlings after 4 days of growth; (B) seedlings after 8 days of growth


**Figure 2.** Shows the growth of root hairs in maize seedlings at different concentrations of nano-calcium: (A) 0.5%, (B) 1%, (C) 1.5%, (D) 2%

**Table 3.** The effects of varying zeolite concentrations on plant germination and growth parameters

| Zeolite concentration | Germination rate (after 4 days) (%) | Germination rate (after 8 days)(%) | Shoot length (cm) | Root length (cm) | Fresh weight (mg) | Dry weight (mg) | Leaves No. |
|---|---|---|---|---|---|---|---|
| 0 | 70 a | 83.33 a | 7.77 b | 14.95 a | 10.89 a | 0.332a | 2.03a |
| 2 | 60 a | 96.67 a | 12.00 a | 15.53 a | 8.60 a | 0.369 a | 2.07 a |
| 5 | 66.67 a | 93.33 a | 11.02 ab | 15.07 a | 14.53 a | 0.364 a | 2.03 a |

3. Experiment 3 – using soil-based germination trays, assess the effects of nano-calcium impregnated zeolite on maize growth.

The third test, which involved application of zeolite containing nano-calcium to the soil using germination trays, showed significant impacts on both biomass and germination rate. As indicated by Table 4, increased germination rate was seen after four days after the application of 2% zeolite, while a reduced germination was realized where the high 5% application was used. By eight days, treatment differences in the germination rates were no longer significant. Additionally, 2% application of zeolite significantly boosted fresh and dry weights in the entire plant, while no significant impacts were realized for the rest of the growth traits that were measured.

Different letters indicate significant differences at a probability of 0.05, according to Duncan's multiple range test.

The effects of zeolite loaded with nano-calcium on maize germination and growth characteristics are shown from the data provided in Table 5. As concentration of the nano-calcium increased, there was a notable reduction in the percentage of germination. The 2% treatment showed the lowest percentage of germination at 65.00%, which was significantly lower compared to the other treatments following four and eight days after sowing. Shoot growth displayed a regular decline following the rise in nano-calcium concentrations, and the highest concentrations had the strongest inhibitory effect. Root growth was also reduced considerably at the 2% concentration, but at low concentrations, an improvement was noted in the elongation of the roots compared to the control, and the 1% concentration achieved the highest root length (11.689 cm). Furthermore, dry biomass also reduced at greater concentrations of nano-calcium. Particularly, dry matter of maize plants declined substantially to 5.30 g from

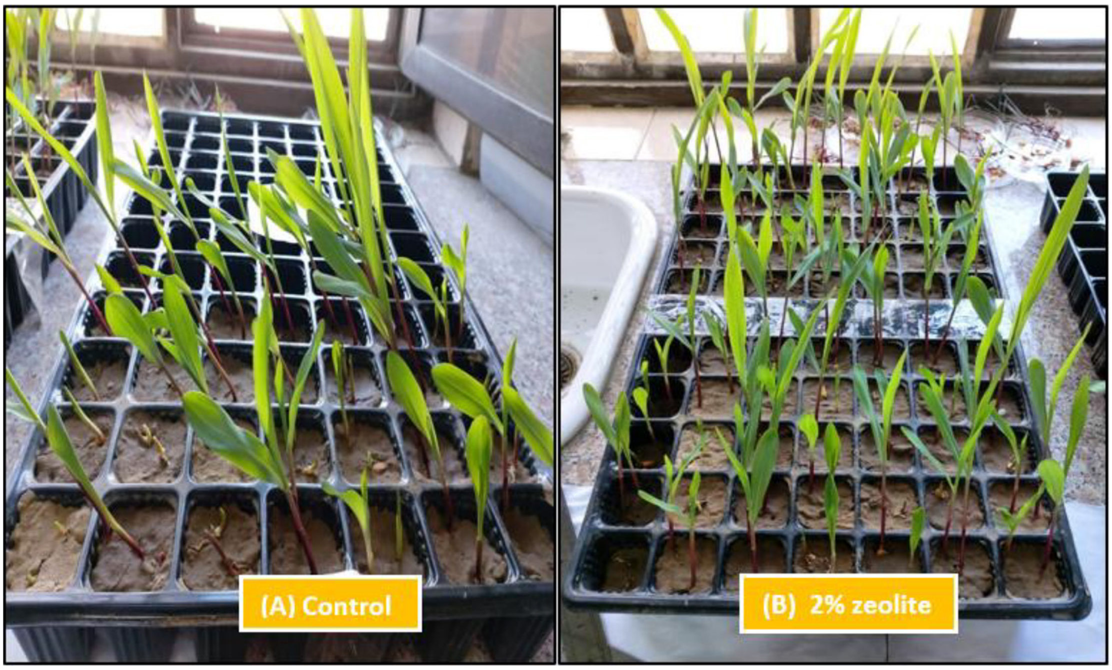


**Figure 3.** Effects of zeolite application on maize growth (A) treated with zero zeolite; (B) modified soil containing two grammes of zeolite per two kilogrammes of soil

**Table 4.** The effects of different zeolite concentrations on the percentage of germination and specific growth characteristics of *Zea mays* in soil-based settings

| Zeolite concentration | Germination rate (after 4 days) | Germination rate (after 8 days) | Shoot length (cm) | Root length (cm) | Fresh weight (mg) | Dry weight (mg) |
|---|---|---|---|---|---|---|
| 2% Zeolite | 91.33a | 94.67 a | 1.81 a | 9.76 a | 8.51 a | 0.823 a |
| 5% Zeolite | 76.00 b | 90.00 a | 1.94 a | 9.15 a | 6.35 b | 0.588 b |

**Table 5.** Impact of nano-calcium concentrations on zeolite on maize growth and germination parameters

| NCa concentration (w/v) (g/L) | Germination rate (after 4 days) | Germination rate (after 8 days) | Shoot length (cm) | Root length (cm) | Fresh weight (mg) | Dry weight (mg) |
|---|---|---|---|---|---|---|
| 0% | 95.00 a | 100.00 a | 2.04 a | 8.66 bc | 7.43 a | 7.17 a |
| 0.5% | 95.00 a | 95.00 a | 2.00 ab | 9.40 b | 7.38 a | 8.14 a |
| 1% | 85.00 b | 95.00 a | 1.80 ab | 11.68 a | 7.63 a | 7.52 a |
| 1.5% | 78.00 b | 95.00 a | 1.78 b | 9.44 b | 7.66 a | 7.14 a |
| 2% | 65.00c | 76.00 b | 1.76 b | 8.11 c | 7.05 a | 5.30 b |

**Table 6.** Interaction effects of concentrations of zeolite and nano-calcium on maize plant germination and growth characteristics

| Zeolite concentration | NCa concentration | Germination rate after 4 days | Germination rate after 8 days | Shoot length (cm) | Root length (cm) | Fresh seedling weight (mg) | Dry seedling weight (mg) |
|---|---|---|---|---|---|---|---|
| 2% | 0% | 93.33 ab | 100.00 a | 1.68 ab | 9.03 cd | 8.27 ab | 0.603 b |
| | 0.5% | 90.00 abc | 100.00 a | 1.94 ab | 10.20 bc | 7.79 abc | 0.633b |
| | 1% | 80.00 abc | 100.00 a | 1.9 ab | 11.23 ab | 8.75 a | 0.585 b |
| | 1.5% | 63.33 d | 96.67 a | 1.87 ab | 9.48 cd | 8.9 a | 0.581 b |
| | 2% | 53.33 d | 76.67 b | 1.67 c | 8.8 cd | 8.82 a | 0.538b |
| 5% | 0% | 96.67 a | 100.00 a | 2.4 a | 8.30 dc | 6.58 bc | 0.832a |
| | 0.5% | 100.00 a | 90.00 ab | 2.05 b | 8.54 dc | 6.97 bc | 0.995 a |
| | 1% | 90.00 ab | 90.00 ab | 1.7 bc | 12.13 a | 6.58 bc | 0.918 a |
| | 1.5% | 93.33 ab | 93.33 ab | 1.69 bc | 9.41 cd | 6.42 cd | 0.846 a |
| | 2% | 76.67 c | 76.67 c | 1.86 c | 7.34 e | 5.28 d | 0.523 b |

the 2% treatment of nano-calcium compared to the other treatments.

Different letters indicate significant differences at a probability of 0.05, according to Duncan's multiple range test.

The interaction between zeolite and nano-calcium concentrations on the germination and growth characteristics of yellow maize seedlings are are presented in Table 6. The simultaneous use of 2% zeolite and nano-calcium significantly lowered seed germination percentages over time. Particularly, the interaction between 2% zeolite and 2% nano-calcium brought about the clearest reductions in the percentage of seed germination after 4 and 8 days and also significant reductions in shoot lengths (53.33 cm), plant heights (76.67 cm), and root lengths (1.67 cm).On the other hand, using 2% zeolite combined with low concentrations of nano-calcium (0.5% and 1%) significantly increased root lengths to 10.20 cm and 11.23 cm, respectively. Moreover, interactions between 2% zeolite and 1%, 1.5%, and 2% concentrations of nano-calcium increased fresh plant weights significantly, although no uniform effects were noted for dry weight. Surprisingly, the highest seed germination percentage (100%) was noted using the interaction between 5% zeolite and 0.5% nano-calcium. Nevertheless, 5% zeolite combined with 2% nano-calcium significantly reduced all growth parameters measured (Figure 4). Moreover, an interaction between 5% zeolite and 1% and 1.5% concentrations of nano-calcium also increased root lengths to 12.13 cm and 9.41 cm, respectively.

Different letters indicate significant differences at a probability of 0.05, according to Duncan's multiple range test.

## DISCUSSION

The findings of the first experiment showed that concentrations of nano-calcium significantly impacted maize seed germination and initial root growth. Germination was reduced at higher concentrations of nano-calcium following four days of sowing, while 0.5% concentration registered the highest percentage of germination (96%), signifying a positive effect at low concentrations. The root elongation also demonstrated significant decline following increased concentrations of nano-calcium, while the highest decline was noted at 2% (Figure 2). Other growth characteristics were not greatly affected, implying that elongation of roots is specially vulnerable to nano-calcium at the initial stages of growth. Germination and root growth decline at high concentrations have been attributed to oxidative stress resulting from the buildup of excessive nanoparticles and production of reactive oxygen species (ROS), which leads to cell damage. Similar results were seen from previous studies that noted that nanoparticles have a dual effect where they are beneficial at moderate doses to enhance growth, while beyond this, they will impair physiological processes such as photosynthesis, flowering, and biomass production (23). Nano-calcium at 0.5% concentration stimulated vital plant processes like membrane stability, enzymatic regulation, and root elongation, signifying the vital role of calcium to establish seed seedlings. Additional evidence from previous studies depicted that moderate application of nano-calcium increased plant height, chlorophyll content, branching, dry matter, and crop yield(25), while high concentrations (e.g., 1 g/L) mostly increased total soluble solids (TSS) of kernel without affecting vegetative growth (26).Overall, these results indicate that moderate concentrations of nano-calcium can enhance initial growth and development of maize while high application may trigger phytotoxicity. Hence, for maximum agronomic potential, management of concentrations of nano-calcium needs to be done very carefully.

The second experiment compared the effect of zeolite application to the soil using seedling trays. A notable decline in shoot growth was seen at the extreme zeolite concentration (5%), while the 2% zeolite treatment provided a significantly higher shoot growth (12 cm) (Table 3) compared to both control and the higher concentration. Other measured attributes were unaffected by zeolite application. The increased shoot growth at 2% zeolite concentration is highly attributed to improved soil physical attributes, mainly water and nutrient availability (Figure 3), which are proven to advance crop growth. Zeolite capacity to serve as a slow supply source for water and nutrients is well-documented. Earlier studies showed that the combination of zeolite and mixing it along with biochar and organic fertilizers significantly increased crop yields for water-stressed conditions. For instance, a study on rice production in Egypt concluded that the combination of zeolite, biochar, and organic amendments supplemented by kaolin and magnesium silicate increased growth considerably by enhancing the capacity to retain soil moisture (27). Similar benefits have also been


**Figure 4.** Effects of 5% zeolite and 2% nano-calcium on the development of maize plants (A) reduced shoot length; (B) reduced root length

documented for maize, where zeolite application increased the efficiency of N usage and triggered root system development (8, 9). On lettuce production, the combination of zeolite and biochar increased biomass accumulation, leaf area, water content, and vitamin C content (28). The present study confirms these reports and supports the use of zeolite to enhance soil conditions to induce better and healthy crop growth.

The third investigation assessed the influence of zeolite loaded with nano-calcium on maize seedlings. There was a notable improvement in percentage germination at 2% zeolite after four days, while at 5% zeolite, germination was significantly reduced (Figure 4). By eight days, treatment-level differences in germination were not significant. Fresh and dry biomass accumulation was also significantly greater with 2% zeolite, while other growth characters were without significant variation. The improved germination and biomass at moderate levels of zeolite may be due to increased water and nutrient retention, enhancing initial seedling vigor. Improved cellular hydration caused by zeolite and nano-calcium is probably the cause of the rise in fresh biomass, even while shoot and root elongation is limited. Nano-calcium raises the turgor pressure and water uptake (29), and zeolite increases the moisture retention in the roots (30). On the other hand, the decrease at high zeolite levels (5%) may be due to soil compaction or altered nutrient dynamics that hamper seedling growth. These findings are consistent with previous reports that zeolite application enhances soil water and nutrient retention and availability, especially under dry land conditions. Independent analysis showed that increased concentrations of nano-calcium reduced the germination rate, and the highest decline was seen at 2% nano-calcium treatment (the lowest percentage of germination being 65%). Shoot and root lengths also reduced upon increased concentrations of nano-calcium, and the maximum decline at 2% was registered. Interestingly, root length increased up to 1% nano-calcium (11.689 cm), indicating dose-responsiveness. Dry biomass also reduced at increased concentrations of nano-calcium, and the lowest value (5.30 g) was reported for 2% treatment. Inhibition at increased concentrations of nano-calcium may be due to nanoparticle-induced oxidative stress and cytotoxicity, which cause chromosomal condensation and cell damage (31). Similar stress responses have been reported, and nanoparticles disrupt crucial physiological processes such as photosynthesis, respiration, and growth. Interaction between zeolite and concentrations of nano-calcium also governed maize seedling responses. Combination of 2% zeolite and 2% nano-calcium resulted in the maximum decline for all the traits at both four and eight days, along with significant reductions in shoot and root lengths (53.33 cm, 76.67 cm, and 1.67 cm, respectively). However, a combination of 2% zeolite and low concentrations of nano-calcium (0.5%, and 1%) significantly improved elongation of the root at 10.2 cm and 11.23 cm, respectively. Fresh biomass production was also greater under 5% zeolite with 1–1.5% concentrations of nano-calcium. These results indicate concentration-dependent interaction between zeolite and nano-calcium, where moderate concentrations produce synergistic effects on seedling performance and high concentrations exhibit inhibitory activity. It is known that high concentrations of zeolite may disrupt soil nutrient release patterns and thus may enhance the availability of calcium beyond the optimum and affect plant growth (25, 32). Notably, even the maximum rate of germination (100%) was registered at the interaction of 5% zeolite and 0.5% nano-calcium. This may be due to zeolite's water-holding and nutrient-regulating capacity and the vital function of calcium for membrane and cell elongation (32). Nevertheless, high concentrations of nano-calcium (2%) and high zeolite (5%) resulted in significant reductions for all the measured traits (33), emphasizing the need to carefully optimize application quantities of nano-fertilizer to avail maximum benefits while avoiding phytotoxic exposure.

## CONCLUSIONS

This research indicates the potential benefit of using nano-calcium and zeolite as soil additives to boost the growth of *Zea mays.* Nano-calcium at a 0.5% concentration strongly facilitated seed germination with its likely positive effects on cellular processes and nutrient absorption. Higher concentrations were found to carry unfavorable impacts, such as impaired root development, possibly owing to induced oxidative stress. Zeolite at 2% had the remarkable effect of enhancing shoot growth through better soil structure and water and nutrient retention capacity. Most notably, the dual use of nano-calcium and zeolite provided a synergy, enhancing plant growth parameters without inducing phytotoxicity. The results in these studies indicate that the combined application of these substances at optimized levels has the potential to be a long-term durable solution to enhance crop performance. Further studies at the optimal concentration and in different-environmental exposures need to be done to ascertain the best approach.

## REFERENCES


1. Méndez Argüello B, Vera Reyes I, Cárdenas Flores A, Santos Villarreal G, Ibarra Jiménez L, Lira Saldivar R. (2018). Water holding capacity of substrates containing zeolite and its effect on growth, biomass production and chlorophyll content of Solanum lycopersicum Mill. *Nova scientia. 10*(21):45–60.
2. Mondal M, Biswas B, Garai S, Sarkar S, Banerjee H, Brahmachari K, et al. (2021). Zeolites enhance soil health, crop productivity and environmental safety. *Agronomy. 11*(3):448.
3. Szatanik-Kloc A, Szerement J, Adamczuk A, Józefaciuk G. (2021). Effect of low zeolite doses on plants and soil physicochemical properties. *Materials. 14*(10):2617.
4. Humadi JI, Saeed LI, Razzaq GHA, Habila MA, Haldhar R. (2025). Green diesel desulfurization process in a basket reactor over eco-friendly tin oxide–ZSM-5 zeolite. *Petroleum Chemistry.* 1–12.
5. Jakkula VS, Wani S. (2018). Zeolites: Potential soil amendments for improving nutrient and water use efficiency and agriculture productivity. *Scientific Reviews & Chemical Communications. 8*(1):1–15.
6. Sharma V, Javed B, Byrne H, Curtin J, Tian F. (2022). Zeolites as carriers of nano-fertilizers: From structures and principles to prospects and challenges. *Applied Nano. 3*(3):163–86.
7. Othman EZ, El-Attar AB, El-Bahbohy RM, Abd El-Khalek SN, Morgan SH, Mahmoud AWM. (2023). Exogenous appliance of nano-zeolite and nano-silicon elevate solidago canadensis invasive plant tolerance to water deficiency. *Horticulturae. 9*(2):172.
8. Ahmed O, Sumalatha G, Muhamad AN. (2010). Use of zeolite in maize (*Zea mays*) cultivation on nitrogen, potassium and phosphorus uptake and use efficiency. *International Journal of the Physical Sciences.5*(15):2393–401.
9. Budiyanto G. (2020). The Application of zeolite to increase nitrogen use efficiency in corn vegetative growth in coastal sandy soils. *PLANTA TROPIKA. 8*(1):1–6.
10. Aiad MA, Amer MM, Khalifa TH, Shabana MM, Zoghdan MG, Shaker EM, et al. (2021). Combined application of compost, zeolite and a raised bed planting method alleviate salinity stress and improve cereal crop productivity in arid regions. *Agronomy. 11*(12):2495.
11. Babaousmail M, Nili MS, Brik R, Saadouni M, Yousif SK, Omer RM, et al. (2022). Improving the tolerance to salinity stress in lettuce plants (*Lactuca sativa* L.) using exogenous application of salicylic acid, yeast, and zeolite. *Life. 12*(10):1538.
12. Romadhan TD, Marwanto M, Murcitro BG, Handajaningsih M. (2022). Amelioration of salinity stressed soil using natural zeolite for improving soil properties and chinese cabbage agronomic performances. *Akta Agrosia. 25*(1):29–38.
13. Hepler PK. (2005). Calcium: a central regulator of plant growth and development. *The Plant Cell. 17*(8):2142-55.
14. Wang Y, Martins LB, Sermons S, Balint-Kurti P. (2020). Genetic and physiological characterization of a calcium deficiency phenotype in maize. *G3: Genes, Genomes, Genetics. 10*(6):1963–70.
15. Gao Y, Chen S, Li Y, Shi Y. (2023). Effect of nano-calcium carbonate on morphology, antioxidant enzyme activity and photosynthetic parameters of wheat (*Triticum aestivum* L.) seedlings. *Chemical and Biological Technologies in Agriculture. 10*(1):31.
16. Arora PK, Tripathi S, Omar RA, Chauhan P, Sinhal VK, Singh A, et al. (2024). Next-generation fertilizers: the impact of bionanofertilizers on sustainable agriculture. *Microbial Cell Factories. 23*(1):254.
17. Roosta HR, Samadi A, Bikdeloo M. (2023). Different cultivation systems and foliar application of calcium nanoparticles affect the growth and physiological characteristics of pennyroyal (*Mentha pulegium* L.). *Scientific Reports. 13*(1):20334.
18. Rehman A, Khan S, Sun F, Peng Z, Feng K, Wang N, et al. (2024). Exploring the nano-wonders: unveiling the role of Nanoparticles in enhancing salinity and drought tolerance in plants. *Frontiers in Plant Science. 14*:1324176.
19. Hussein AM, Ibraheem FF, editors. (2023). Effect of Soaking Tubers in Potassium Humate and Foliar Application of Nano-Calcium Fertilizer on some Growth Traits of Two Potato Cultivars. *IOP Conference Series: Earth and Environmental Science; IOP Publishing.*
20. Jarosz R, Szerement J, Gondek K, Mierzwa-Hersztek M. (2022). The use of zeolites as an addition to fertilisers – A review. *Catena. 213*:106125.
21. Antonoglou S, Koutroubas SD, Antoniadis V, Damalas CA, Fotiadis S, Markopoulos T. (2025). Zeolite enhances the beneficial effects of sewage sludge on barley yield, increases nitrogen use, and improves soil properties. *Journal of Soil Science and Plant Nutrition.* 1–14.

22. Tian Y, Guan B, Zhou D, Yu J, Li G, Lou Y. (2014). Responses of seed germination, seedling growth, and seed yield traits to seed pretreatment in maize (*Zea mays* L.). *The Scientific World Journal. 2014*(1): 834630.
23. Al-Zubaidy MH. (2021). Akutna neurotoksičnost acetaminofena u pilića. *Veterinarski arhiv. 91*(4):379-87.
24. Duncan DB. (1955). Multiple range and multiple F tests. *Biometrics. 11*(1):1–42.
25. Alrashedy AMH. (2023). *Effect of soaking tubers with potassium humate and spraying with nano-calcium fertilizer on growth, yield, storage, and anatomical characteristics of two potato cultivars* (*Solanum tuberosum* L.): University of Mosul.
26. Tantawy A, Salama Y, Abdel-Mawgoud M, Ghoname A. (2014). Comparison of chelated calcium with nano calcium on alleviation of salinity negative effects on tomato plants. *Middle East Journal of Agriculture Research. 3*(4):912–6.
27. Ghazi D, Hafez S. (2023). Rice cultivation adaption to water resources shortage in Egypt. *Egyptian Journal of Soil Science. 63*(1):113–26.
28. Agb E, Kaney M. (2024). Improving crisphead lettuce productivity grown under water deficit conditions through biochar and zeolite soil amendments, coupled with foliar stimulant applications under a drip irrigation system. *Egyptian Journal of Soil Science. 64*(2).
29. Raiesi Ardali T, Soleimanpour L, Mamani L, Chorom M. (2024). Opportunities and future perspective of nanofertilizers and controlled release nanofertilizers in agriculture. *Journal of Water and Environmental Nanotechnology. 9*(2):223–47.
30. Idim KS, Marzi M, Oyeyiola A, Kazemian H. (2024). Enhancing composting efficiency and nutrient retention through zeolite amendment: implications for sustainable soil management and plant growth. *ACS Sustainable Resource Management. 1*(7):1340–9.
31. Salem KF, Alloosh MT, Saleh MM, Alnaddaf LM, Almuhammady AK, Al-Khayri JM. (2021). Utilization of nanofertilizers in crop tolerance to abiotic stress. *Nanobiotechnology: Mitigation of Abiotic Stress in Plants.* 261–89.
32. Nakhli SAA, Delkash M, Bakhshayesh BE, Kazemian H. (2017). Application of zeolites for sustainable agriculture: a review on water and nutrient retention. *Water, Air, & Soil Pollution. 228*:1–34.
33. Kumar V, Sharma M, Khare T, Wani SH. (2018). Impact of nanoparticles on oxidative stress and responsive antioxidative defense in plants. *Nanomaterials in plants, algae, and microorganisms*, 393–406.