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Nanoparticle-mediated modulation on growth and yield of soybean under salinity stress

Most. Tanjina Akter[1], Md. Abdul Mannan[1*], Md. Abdullah Al-Mamun[1] and Masuma Akter[1]

[1] Department of Agronomy, Gazipur Agricultural University, Gazipur-1706, Bangladesh.

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ABSTRACT

One of the major problems affecting soybean growth and productivity is salinity stress, which lowers plant height, number of leaves, biomass, and yield, particularly in areas affected by salt. To improve salinity tolerance of soybean and sustain growth, development, and yield, this study examined the potential benefits of foliar spray of Iron (II,III) oxide (Fe_3O_4), Zinc oxide (ZnO), Titaniun oxide (TiO_2), and Magnesiun oxide (MgO) nanoparticles (NPs). The pot experiment was laid out at the Department of Agronomy, Gazipur Agricultural University, Bangladesh, during the *Rabi* season of 2023–2024 following a completely randomised design with three replications. Five nanoparticle treatments - control (no nanoparticles), Fe_3O_4, ZnO, TiO_2, and MgO - each applied at a concentration of 200 ppm, along with two salinity levels [control (0 mM NaCl) and 50 mM NaCl], were used in the experiment. The substantial negative effects of salinity on plant growth and yield was observed. Plant height, number of leaves, total dry weight, and seed yield were decreased by 38%, 56%, 64%, and 54%, respectively compared to the control plants. Nanoparticles mitigated the negative effects of salinity. Among the NPs, ZnO showed the best performance, boosting plant height by 59%, number of leaves by 53%, and seed yield by 46%. whereas biomass reduction was only 19% compared to the non-treated saline affected plants. MgO also improved plant performance under salinity. TiO_2 and Fe_3O_4 showed moderate effects. These results indicate that ZnO and MgO nanoparticles effectively minimised the growth and yield losses of soybeans under salinity. Future studies should elucidate the physiological, biochemical, and molecular mechanisms of NP-mediated salinity tolerance in soybean.

*Corresponding Author: Department of Agronomy, Gazipur Agricultural University, Gazipur-1706, Bangladesh. Email: mannanagr@gau.edu.bd

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Introduction

Soybean (*Glycine max* L.), also known as the "miracle crop" or "golden bean" of the twenty-first century (Tambe *et al*., 2021), has both its nutritional and economic importance. It is commonly used in aquaculture, poultry, and cattle feed and is an important source of protein and oil for human consumption (Haque *et al*., 2020). Because the agroclimatic conditions of Bangladesh's coastal region is ideal for growing soybeans is a viable way to boost cropping intensity and production in these locations. However, soybeans are extremely susceptible to salt, which eventually reduces growth and yield by interfering with ion balance, water uptake, and nutrient absorption (Mannan *et al*., 2012).

According to El-Moy *et al*. (2018), one of the most serious abiotic factors limiting crop production globally is soil salinity. It reduces global crop production by 30% and impacts plants at every stage of growth, from germination to harvest (Machado and Serralheiro, 2017). According to Lhissoui and El Harti (2014), salinization affects over one billion hectares worldwide and is growing by about two million ha per year. Approximately 20% of farmed land and 7% of all land on Earth currently experience salinity stress, especially in dry and semi-arid areas (Scudiero *et al*., 2016). In Bangladesh, approximately 70% of coastline arable land, or 1.02 million ha of lands are affected by varies degree of salinity (Ashrafuzzaman *et al*., 2022). By 2050, it is predicted that more than half of the world's arable land would have become salinized, which is concerning (Alzahrani *et al*., 2021).

Salinity disrupts physiological and biochemical functions of plants, such as photosynthesis, protein synthesis, respiration, and lipid metabolism (Abdeldym *et al*., 2020). According to Abdelgawad *et al*. (2019), reduction in leaf expansion of plants is one of the initial responses to salt stress, which limits shoot growth. These effects are mostly caused by osmotic stress and ion toxicity, particularly from Na^+ and Cl^-. Salinity causes oxidative damage, change the nitrogen balance, and create physiological drought by decreasing the osmotic potential of soils (Almeida *et al*., 2017). To cope up with salinity stress, plants accumulate soluble sugars, amino acids, and proline that maintain cellular homeostasis and osmotic balance (Khan *et al*., 2019). An excessive buildup of Na^+ creates an excess of reactive oxygen species (ROS), including as hydroxyl radicals (•OH), hydrogen peroxide (H_2O_2), and superoxide radicals ($O_2^{\bullet -}$). These ROS oxidize lipids, disorganize membranes, and disrupt metabolic processes (Ahmad *et al*., 2020). To sustain normal physiological processes and crop production capacity of plants efficient oxidative stress control is necessary.

Nanoparticles (NPs), which are typically between 1 and 100 nm in size, have high surface area and reactivity. Due to these unique physicochemical properties NPs can interact with plant systems effectively (Maghsoodi *et al*., 2020). Through enhanced

K^+ absorption, decreased Na^+ toxicity, ion balancing, antioxidant defence activation, cell membrane stabilization, and increased osmolyte and chlorophyll content, foliar or soil application of NPs can help plants tolerate salt stress (Rajput *et al*., 2021). It has been reported that a number of nanoparticles, such as nano-silicon, CeO_2, and ZnO, lessen the impacts of salinity in different crops like tomatoes and *Brassica napus* (Almutairi, 2016; Rossi *et al*., 2017). SiO_2 and Fe_3O_4 nanoparticles have also been shown to promote growth in soybean and lupin under stress conditions (Merwad *et al*., 2018; Dola *et al*., 2022).

Although encouraging, the majority of earlier research has only been done in hydroponic or laboratory settings; very few studies have been done in soil-based simulated saline conditions, especially for soybeans in Bangladesh. Furthermore, despite the potential for increasing productivity under salinity stress, comparative assessments of various nanoparticle kinds on soybean growth and production are still rare. By enhancing ion homeostasis, antioxidant activity, and osmotic management in saline soil, it is hypothesized that foliar application of particular nanoparticles (ZnO, Fe_3O_4, TiO_2, and MgO) can variably boost soybean growth and yield. The goal of the study is to find out the best kind of nanoparticle to reduce salinity stress and boost soybean growth and production in simulated saline soil conditions.

Materials and Methods

Experimental location

A pot experiment was conducted in *Rabi* season during November 2023 to February, 2024 in the stress research site, Department of

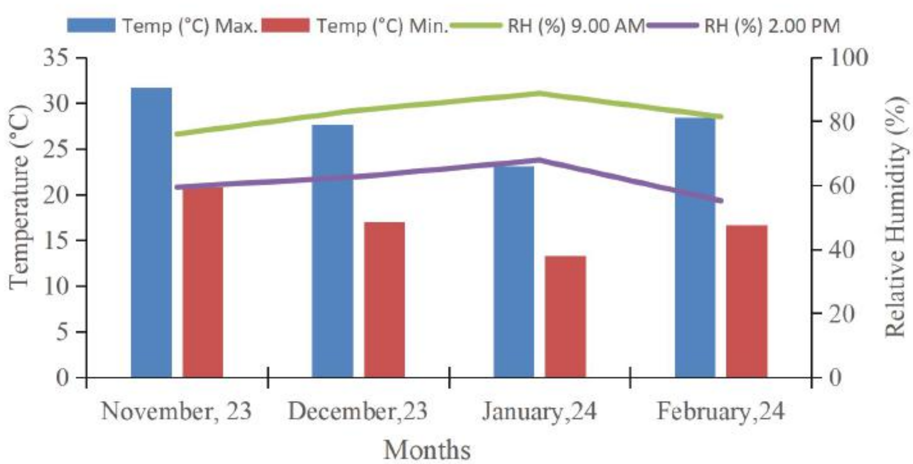

Fig. 1. Average temperature and humidity during experimentation

Agronomy, Gazipur Agricultural University, Gazipur. Bangladesh (8.4 meters above mean sea level at latitude 24° 5′ 23″ N and longitude 90° 15′ 36″ E). Average monthly maximum and minimum temperature, and relative humidity during experimentations are presented in Fig. 1 (GAU, 2024).

The soil of the experimental pot had a pH of 6.37 and a sandy loam texture, consisting of 52.51% sand, 32.00% silt, and 15.49% clay. Soil organic carbon, available P, total N, exchangeable K, CEC, and EC values were, in that order, 0.52%, 0.067 mg 100^{-1} g, 0.069%, 0.729 cmol kg^{-1} dry soil, 12.70 cmol kg^{-1} dry soil, and 0.02 dS m^{-1}.

Agronomic practices

Each plastic container (30 cm × 24 cm) was filled with 11 kg of a 4:1 mixture of air-dried soil and cow dung. Following the Fertilizer Recommendation Guide (FRG, 2018), 0.32 g of urea, 0.933 g of triple superphosphate (TSP), and 0.64 g of muriate of potash (MOP) were uniformly applied to each pot, corresponding to field-equivalent rates of 20 kg urea, 70 kg TSP, and 40 kg MOP ha^{-1}e, respectively. Weeds were controlled by hand weeding as well as the pest and disease infestations were managed with recommended chemical control measures. Fungicides and insecticides were applied following standard protocols when necessary.

Experimental design and treatments

The experiment was conducted in a polyhouse using a Completely Randomized Design (CRD) with three replications. It involved two factors: salinity levels and nanoparticle treatments. Factor A consisted of two salinity levels - control (0 mM NaCl) (irrigation with tap water) and saline (irrigation with a 50 mM NaCl saline solution). Factor B comprised five nanoparticle treatments - no nanoparticle (Foliar spray with distilled water), Fe_3O_4, ZnO, TiO_2, and MgO NPs - each applied at a concentration of 200 ppm.

Nanoparticles solutions preparation

Fe_3O_4, ZnO, TiO_2, and MgO nanopowders were used to prepare NPs suspensions. To formulate 200 ppm solutions, 200 mg of each commercial nanopowder (Sigma Aldrich, Germany; mean particle size ≤50 nm; BET surface area 50 - 80 m^2 g^{-1}) was accurately weighed using an analytical balance. Each measured amount was transferred into a 1000 mL beaker containing approximately 800 mL of deionized water. The suspensions were initially stirred for 30 minutes with a magnetic stirrer to achieve preliminary dispersion, followed by ultrasonication at 40 kHz for 30 minutes immediately before application to ensure homogeneity. After sonication, each suspension was transferred into a 1000 mL volumetric flask, and the final volume was adjusted to 1000 mL with deionized water. The prepared suspensions were stored at 4 °C and used within 7 days. Before application, each solution was vortexed, and the required amount was poured into a hand sprayer for foliar application to the plants.

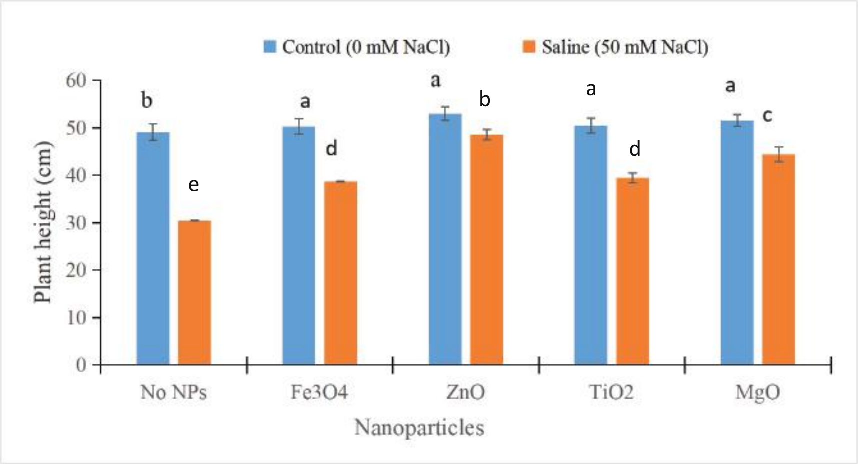

Fig. 2. Influence of various nanoparticles on plant height of soybean under salinity stress. Bars indicate (±SE)

Crop cultivation and treatment imposition

A total of 200 g of mature BU Soybean-2 seeds were randomly selected and surface-sterilized in 1% sodium hypo chloride (NaOCl) for 5 minutes, then thoroughly rinsed with distilled water and air-dried to restore their original moisture content. Ten seeds were sown in each pot on November 15, 2023, and then the plants were softly moistened with tap water to ensure consistent germination. When the seedlings reached the trifoliate leaf stage, which was 14 days after sowing (DAS), they were trimmed to six plants per container. The pots were moved at random inside each block each week, and weeds were hand-pulled as necessary. Salinity stress was first imposed at the trifoliate stage using a 50 mM NaCl solution and was maintained throughout the entire growing season through irrigation as required; while the control pots were irrigated twice a week with tap water (0 mM NaCl). Different NPs at 200 ppm concentration solutions were foliar-applied seven days later, with two applications made during that week. Control plants were sprayed with tap water.

Data collection

Growth and yield data were recorded at two different times. Measurements were made 15 days after foliar treatment to determine plant height, number of leaf per plant, dry weights of leaves, stems, roots, immature pods, and total biomass. At maturity, the number of pods per plant, the number of seeds per pods, the 100-seed weight, and the seed yield per plant were all noted. Plant performance under salinity stress was assessed using the stress tolerance (TOL) and yield stability index (YSI). Stress tolerance was calculated as TOL = Yp - Ys (Rosielle and Hamblin, 1981), and YSI was calculated as YSI = Ys / Yp (Bouslama and Schapaugh, 1984), where Yp and Ys represent grain yield under non-stress (control) and salinity stress conditions, respectively.

Statistical analysis

All collected data were analyzed using analysis of variance (ANOVA). Treatment means were compared using the least significant difference (LSD) test at a 5% significance level ($p = 0.05$) following Gomez and Gomez (1984). Statistical analyses were conducted using CropStat 7.2, while graphical representations were prepared in Microsoft Excel 2016. Pearson's correlation analysis was performed using R software to examine the relationships among the traits and treatments evaluated.

Results

Effect of different nano-particles on plant height and number of leafs of soybean under salinity

Plant height

The effect of different NPs at 200 ppm concentration on the plant height of soybean under control (0 mM NaCl) and saline (50 mM NaCl) conditions is presented in Fig. 2. Salinity stress markedly reduced plant height in all treatments. In the untreated control, plant height decreased from 49.06 cm under non-saline conditions to 30.43 cm under salinity, representing a 38% reduction. Application of NPs improved plant height under both control and saline conditions. Under salinity, the highest plant height was recorded with ZnO NPs (48.50 cm), followed by MgO (44.42 cm), TiO_2 (39.38 cm), and Fe_3O_4 (38.66 cm). Compared with the untreated saline control, ZnO increased plant height by 59%, MgO by 46%, TiO_2 by 29%, and Fe_3O_4 by 27%. In non-saline conditions, NPs application resulted in a small improvement in plant height, with ZnO-treated plants reaching the tallest plants (52.94 cm). In general, ZnO NPs outperformed MgO, TiO_2, and Fe_3O_4 nanoparticles in mitigating the negative effects of salinity on soybean plant height

Fig. 3. Plant height of soybean under salinity stress as influenced by different NPs

Number of leaf

The number of leaf of soybean was considerably impacted by salinity stress (Fig. 4). Leaf numbers under control ranged from 8.67 to 10.00. ZnO NPs-treated plants had the most leaves (10.00), followed by untreated plants (9.00), Fe_3O_4 NPs (9.33), and MgO NPs (9.00). The lowest leaf number under control conditions was observed in TiO_2 NPs-treated plants (8.67). Under saline conditions, all treatments showed a reduction in leaf number. Untreated plants exhibited the most severe decline, producing only 4 leaves. Among NPs treatments, ZnO NPs maintained the highest leaf number (8.67), followed by MgO (8.00), TiO_2 (7.00), and Fe_3O_4 (6.00), indicating their potential to alleviate salinity-induced leaf reduction.

Effect of different nanoparticles on dry matter accumulation of different plant parts of soybean under salinity

The effects of different NPs on the dry biomass of soybean under control and saline conditions are presented in Table 1.

Leaf dry weight

Salinity stress markedly reduced leaf dry weight compared with the control. The reduction was most severe (70%) in plants without NPs treatment. Foliar application of NPs at 200 ppm improved leaf biomass under salinity, with the smallest reduction observed in ZnO (7%) and MgO (5%) treatments, followed by Fe_3O_4 and TiO_2 (12% each). These results indicate that ZnO and MgO NPs were most effective in maintaining leaf biomass under saline conditions.

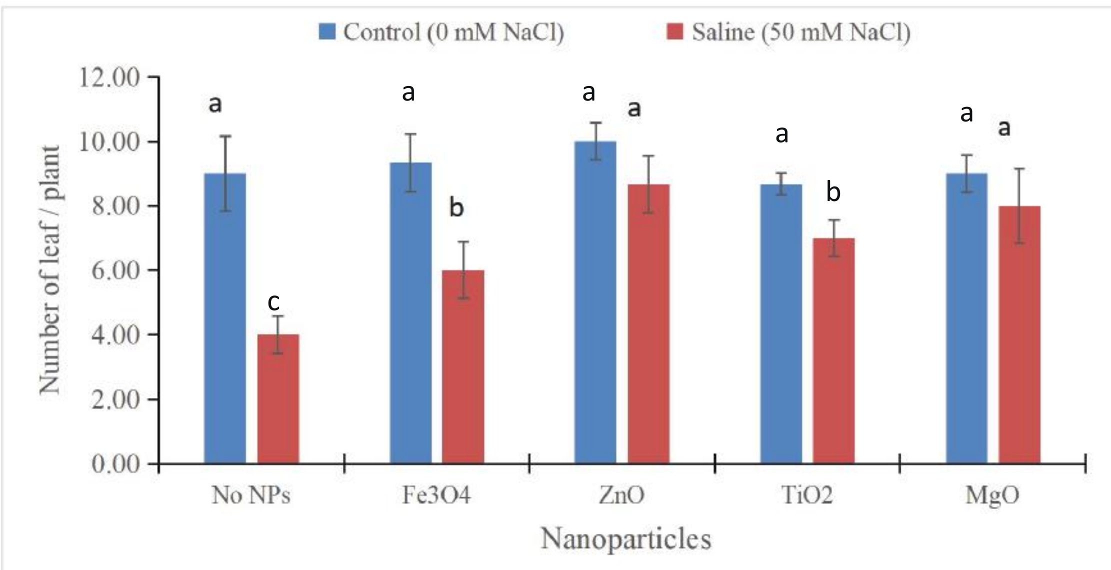

Fig. 4. Influence of various nanoparticles on number of leaves of soybean under salinity. Bars indicate (±SE).

Stem dry weight

Stem biomass was greatly affected by salinity, with untreated plants showing a 64% reduction. Foliar application of ZnO nanoparticles helped reduce this loss to 27%, followed by Fe_3O_4 (37%), MgO (39%), and TiO_2 (45%). Among the NPs, ZnO was the most effective in alleviating the negative effects of salinity on stem growth.

Root dry weight

Root dry weight was the most severely affected by salinity stress, declining by 78% in plants without NPs. Among NP treatments, ZnO exhibited the lowest reduction (41%), followed by MgO (52%), Fe_3O_4 (64%), and TiO_2 (74%). These results demonstrate that ZnO NPs effectively improved root growth under saline conditions.

Immature pod dry weight

Salinity significantly decreased immature pod dry weight, with a 51% reduction in untreated plants. The smallest losses occurred in ZnO (21%) and MgO (27%) treatments, whereas TiO_2 and Fe_3O_4 showed moderate effects with 30% and 52% reductions, respectively. ZnO and MgO NPs thus contributed to improved reproductive growth under salinity stress.

Total dry weight

A significant reduction (64%) in total dry weight due to salinity stress was observed (Table 1). Foliar applied NPs reduced this loss. Plants treated with ZnO had the smallest reduction (19%), followed by those treated with MgO (24%), TiO_2 (31%), and Fe_3O_4 (33%). ZnO nanoparticles showed the best overall defence against the loss of biomass

Table 1. Effect of nanoparticles on leaf dry weight, stem dry weight, root dry weight, immature pod dry weight and total dry weight of soybeans under saline conditions

Nanoparticles at 200 ppm concentrations	Leaf dry wt. (g)		Stem dry wt. (g)		Root dry wt. (g)		Pod dry wt. (g)		Total dry wt. (g)	
	Control (0 mM NaCl)	Saline (50 mM NaCl)	Control (0 mM NaCl)	Saline (50 mM NaCl)	Control (0 mM NaCl)	Saline (50 mM NaCl)	Control (0 mM NaCl)	Saline (50 mM NaCl)	Control (0 mM NaCl)	Saline (50 mM NaCl)
No NPs	1.98a	0.59c (-70)	1.06a	0.38b (-64)	0.49b	0.11e (-78)	1.3a	0.63d (-51)	4.82b	1.71f (-64)
Fe_3O_4	2.03a	1.79b (-12)	1.02a	0.64a (-37)	0.62a	0.22d (-64)	1.33a	0.64d (-52)	5.00a	3.35e (-33)
ZnO	2.04a	1.90b (-7)	1.09a	0.80a (-27)	0.73a	0.43c (-41)	1.35a	1.06b (-21)	5.21a	4.19c (-19)
TiO_2	2.02a	1.78b (-12)	1.02a	0.56a (-45)	0.55b	0.14e (-74)	1.31a	0.92c (-30)	4.90b	3.39e (-31)
MgO	1.95a	1.85b (-5)	1.08a	0.66a (-39)	0.71a	0.34c (-52)	1.34a	0.98b (-27)	5.07a	3.83d (-24)
CV (%)	4.5		4.8		15.2		6.6		3.4	

(-) values in parenthesis indicate percent decrease compared to the control. Values followed by the same lowercase letter within a column are not significantly different at $P \leq 0.05$ (LSD test).

caused by salinity stress, followed by MgO and FeO_4. Salinity significantly reduced soybean growth and biomass accumulation. However, foliar application of nanoparticles, especially ZnO and MgO, effectively reduced these negative effects under saline conditions, improving vegetative development and overall plant performance.

Impact of NPs on yield and yield-related characteristics

Yield and yield contributing parameters of soybean are influenced by 200 ppm different nanoparticles under saline (50 mM NaCl) and control (0 mM NaCl) conditions presented in Table 2.

Number of pods on each plant

When soybeans plants were grown under saline conditions without NPs spraying, the number of pods per plant decreased significantly-from 25.33 under control conditions to 12.67 under saline conditions, a 50% decrease. The decline was lessened by the foliar spraying of NPs. Among the NPs, plants treated with ZnO produced the highest number of pods under saline conditions (24.67), followed by plants treated with MgO (22), TiO_2 (20.33), and Fe_3O_4 (17.33). Comparing all NPs treatments to untreated saline plants, the number of pods per plant increase, demonstrating the beneficial effects of these treatments on reproductive growth under salt stress.

Number of seeds pod^{-1}

There was no significant difference on number of seeds pod^{-1} due to application of different NPs. Number of seeds pod^{-1} reduced in the saline treated plants compared

Table 2. Effect of nanoparticles on number of pods/plant, number of seeds/pod, 100-seed weight and seed yield/plant of soybeans under saline conditions

Nanoparticles at 200 ppm concentrations	Number of pods plant^{-1}		Number of seeds pod^{-1}		100-seed weight (g)		Seed yield (g) plant^{-1}	
	Control (0 mM NaCl)	Saline (50 mM NaCl)	Control (0 mM NaCl)	Saline (50 mM NaCl)	Control (0 mM NaCl)	Saline (50 mM NaCl)	Control (0 mM NaCl)	Saline (50 mM NaCl)
No NPs	25.33a	12.67c (-50)	1.57	1.21 (-23)	15.35a	11.59b (-90)	9.63a	4.45c (-54)
Fe_3O_4	24.00a	17.33b (-28)	1.58	1.41 (-11)	15.74a	11.79b (-25)	10.22a	4.95b (-52)
ZnO	30.00a	24.67a (-18)	1.59	1.55 (-3)	16.28a	15.27a (-6)	10.88a	6.48b (-40)
TiO_2	24.00a	20.33b (-15)	1.51	1.50 (-1)	15.63a	12.90b (-17)	10.50a	5.84b (-44)
MgO	28.67a	22a (-23)	1.55	1.53 (-1)	15.57a	13.95a (-10)	10.16a	6.08b (-40)
CV (%)	16.0		11.5		9.6		14.0	

(-) values in parenthesis indicate percent decrease compared to the control. Values followed by the same lowercase letter within a column are not significantly different at $P \leq 0.05$ (LSD test).

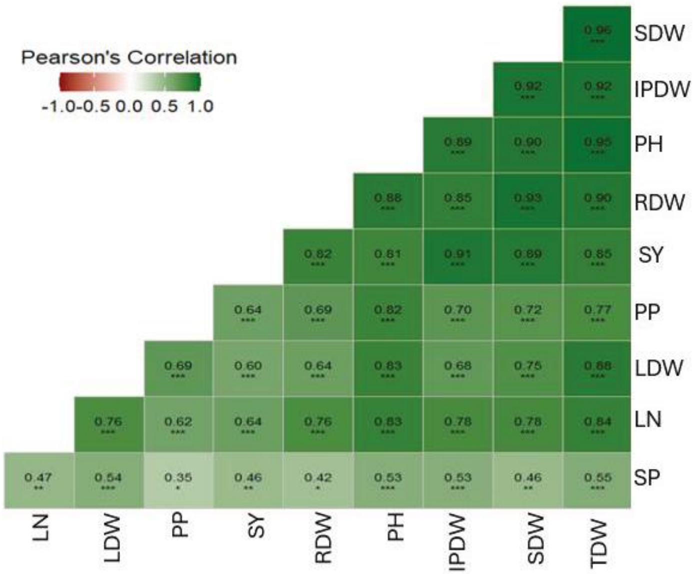

Fig. 5. Pearson's correlation coefficients among various traits were assessed under both control and saline conditions in soybean. Correlated marked with ns = non- significant at P > 0.05; * = significant at P ≤ 0.05; ** = highly significant at P ≤ 0.01; *** = very highly significant at P ≤ 0.001. The evaluated traits include leaf number (LN), leaf dry weight (LDW), pod per plant (pp), seed yield (SY), root dry weight (RDW), plant height PH), immature pod dry weight (IPDW), stem dry weight (SDW), and total dry weight (TDW).

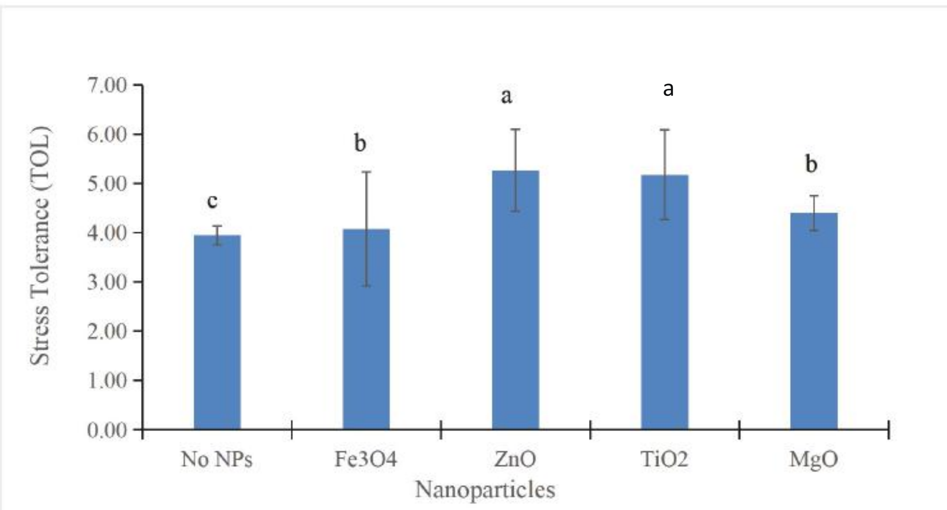

Fig. 6. Effect of different nanoparticles on stress tolerance of soybean under salinity stress. Bars indicate (± SE).

to untreated control from 1.57 to 1.21 (23% reduction). NPs application mitigated the negative effects of salinity, with ZnO (1.55) and MgO (1.53) showing minimal reduction, TiO_2 (1.50) moderate, and Fe_3O_4 (1.41) the least improvement. These results suggest that NPs help maintain pod bearing capacity of soybean under salinity stress.

100-seed weight

Salinity stress significantly decreased 100-seed weight in untreated plants from 15.35 g to 11.59 g. NP treatments alleviated this reduction, with ZnO showing the least decline (16.28 g to 15.27 g), followed by MgO (15.57 g to 13.95 g), TiO_2 (15.63 g to 12.90 g), and Fe_3O_4 (15.74 g to 11.79 g). This indicates that nanoparticles may enhance seed filling and assimilate partitioning under salt stress.

Seed yield plant^{-1}

Seed yield plant^{-1} was severely affected by salinity in untreated control plants, decreasing from 9.63 g to 4.45 g (54% reduction). NP application improved yield under saline conditions, with ZnO-treated plants achieving the highest yield (6.48 g), followed by MgO (6.08 g), TiO_2 (5.84 g), and Fe_3O_4 (4.95 g). This demonstrates that NPs can partially mitigate salinity-induced yield losses in soybean.

Person's correlations

The Pearson's correlation coefficients among different growth and yield parameters of soybean are presented in Fig. 5. Leaf number (ln) showed strong positive correlations with leaf dry weight (r = 0.76), stem dry weight (r = 0.78), root dry weight (r = 0.76), and total

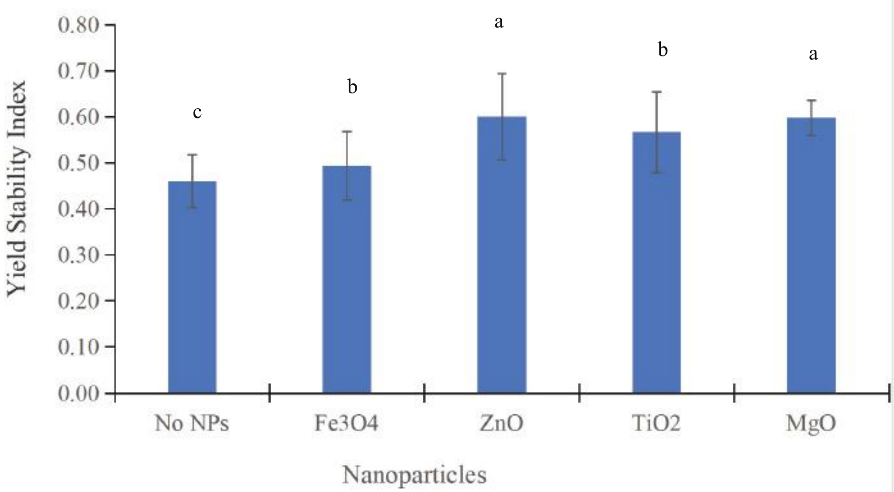

Fig. 7. Effect of different nanoparticles on yield stability index of soybean under salinity stress. Bars indicate (± SE).

dry weight (r = 0.84). A highly significant correlation was observed between total dry weight and all dry matter components, particularly with stem dry weight (r = 0.96) and immature pod dry weight (r = 0.92). Immature pod dry weight (r = 0.91), stem dry weight (r = 0.89), total dry weight (r = 0.85), and root dry weight (r = 0.82) showed the largest positive associations with seed yield (SY). The number of pods per plant (r = 0.64), 100-seed weight (r = 0.78), and leaf number (r = 0.64) all showed moderate correlations with seed yield. There was the least amount of association between seed yield and the number of seeds per pod (r = 0.46).

Stress tolerance

Effects of different nanoparticle treatments on the salinity tolerance index (TOL) of soybean is shown in Fig. 6. There were distinct differences in TOL among the treatments. The highest TOL (5.27) was observed in the plants which were treated with ZnO nanoparticles, closely followed by TiO_2 (5.18). Moderate tolerance was observed in plants treated with MgO (4.40) and Fe_3O_4 (4.08), while the lowest TOL was recorded in untreated plants (3.95). The analysis implies that ZnO and TiO_2 nanoparticles were the most effective in improving salinity tolerance in soybean.

Yield stability index

Among the various nanoparticle treatments, there were notable differences in the soybean yield stability index (YSI) (Fig. 7). Because of their increased susceptibility to salinity stress, plants without nanoparticle application had the lowest YSI (0.46).

YSI was marginally improved to 0.49 after treatment with Fe_3O_4 nanoparticles, suggesting just a minor improvement in yield stability. However, ZnO and MgO nanoparticles had the highest YSI values (0.60), followed by TiO_2 (0.57), indicating that they were the best at preserving yield stability in saline environments.

Discussion

Plant height

Salinity stress dramatically decreased the height of soybean plants (Fig. 2), which is in line with other research that found salt suppresses vegetative development by preventing cell elongation, lowering turgor pressure, and interfering with nutrient uptake (Parida and Das, 2005; Munns and Tester, 2008). The substantial drop in height observed in untreated plants indicate the severity of the osmotic and ionic stress caused by NaCl, which hinders water transport and metabolic functions. Foliar application of NPs reduced these negative impacts. ZnO nanoparticles improved the metabolic functions, which increase plant height that was nearly similar to non-saline controls. According to studies by Rizwan *et al*. (2019) and Mahajan and Kaushik (2020), ZnO NPs enhance antioxidant defence, nutrient uptake, and chlorophyll content, which in turn promotes salinity tolerance. Zinc influenced auxin metabolism and enzyme activation, which are essential for cell growth and elongation. MgO NPs greatly increased plant height because magnesium is necessary for chlorophyll and photosynthesis, which improve carbon uptake and vegetative growth in stressful conditions (Hosseini *et al*., 2019). Farooq *et al*. (2020) observed photosynthesis was somewhat increased and stress-related enzymes were activated by TiO_2 and Fe_3O_4 nanoparticles in stressed plants. Our findings show that nanoparticles, particularly ZnO and MgO, may effectively overcome the growth restriction caused by salt.

Munns and Tester (2008) affirm that stress affects the beginning of leaves, vegetative development, and cell division. In our results we found that salinity decreased the number of leaves on untreated plants. This effect was mitigated by NPs treatments. Among the NPs, ZnO demonstrated the most noticeable improvement. This could be due to improved nutrient uptake, osmotic adjustment, and antioxidant activity, all of which support leaf development and preserve cell turgor (Dimkpa *et al*., 2017; Raliya *et al*., 2015). Furthermore, Fe_3O_4 offered moderate advantages through enhanced iron availability and enzymatic activity (Khan *et al*., 2019), whereas MgO and TiO_2 increased the number of leaves, most likely by shielding chloroplasts and enhancing photosynthetic efficiency (Sharma *et al*., 2020). According to Tripathi *et al*. (2017), these findings imply that ZnO and MgO NPs improve vegetative development and may increase yield stability in salt affected crops.

Dry matter accumulation

Soybean growth was severely suppressed by salinity stress, resulting in large biomass losses in all plant parts in our study (Table 1) but foliar spraying of different NPs significantly lessens the decrease of dry matter accumulation. ZnO and MgO treatments showed the least reductions by 7% and 5%, respectively. This is in line with the research findings of Gupta *et al*. (2024), showing ZnO NPs increase photosynthetic efficiency and lower oxidative stress, which results in increased leaf biomass.

The stem biomass of untreated plants dropped by 64% when soybean plants were exposed to salinity; however, ZnO NPs reduced this reduction to 27%, fast followed by Fe_3O_4 (37%), MgO (39%), and TiO_2 (45%). This suggests that ZnO can sustain the growth of stem cells. The root biomass was reduced by 78% in the untreated salt affected plants. ZnO NPs sustain root development under stress was the highest, followed by MgO, Fe_3O_4, and TiO_2, as demonstrated by the lowest loss of any of the nanoparticles applied.

Pod dry weight decreased by 51% in untreated plants when exposed to salinity. NPs encourage reproductive development under salt stress. While TiO_2 and FeO_4 treatments achieved reductions of 31% and 33%, respectively, ZnO and MgO treatments reduced the loss by 19% and 24%. In untreated plants, the total dry weight decreased by 64 percent. Our finding was corroborating with the findings of the results of Ashraf *et al*.

(2025), who stated that nanoparticles offer the best defence against salt-induced biomass loss.

Yield and yield-contributing parameters

Yield and yield components of soybean suffered from salinity in our research, which is in line with the research of Ferdous *et al*. (2018), who observed that salt stress restricts pod set, seed filling, and total yield by interfering with water relations, nutrient balance, and photosynthesis. The application of nanoparticles greatly reduced these effects. It was observed that NPs preserved the number of pods, number of seeds, 100-seed weight, and seed yield by boosting antioxidant enzyme activity, decreasing oxidative damage, and preserving cellular homeostasis (Hosseini *et al*., 2019; Farooq *et al*., 2020), where ZnO nanoparticles were the most effective. Because of its function in iron-mediated metabolism and chlorophyll production, Fe_3O_4 exhibited mild effects. In general, ZnO and MgO NPs have shown the greatest potential for maintaining soybean yields under salt stress, bolstering crop resilience tactics based on nanotechnology.

Pearson's correlations

There were strong positive correlations found between the dry weight of biomass and seed yield, suggesting that enhanced vegetative growth is crucial for successful reproduction. The substantial connection ($r = 0.91$) between seed yield and immature pod dry weight indicates the importance of good assimilate transport to reproductive organs. Its application as a criterion for breeding selection was proven by its substantial connection with both total dry weight and seed output (Patel *et al*., 2021). However, the correlation for seeds per pod was weaker ($r = 0.46$), indicating that this attribute is more genotype-specific. These findings highlight the importance of preserving vegetative vigour and biomass such as stem dry weight, and total dry weight impact efficiency in order to increase production under stress.

Stress tolerance (TOL)

ZnO and TiO_2 treatments had the greatest TOL values, demonstrating their effectiveness in reducing the negative effects of salt stress. ZnO nanoparticles (NPs) contribute to membrane stabilization, enhance photosynthetic efficiency, regulate Na^+/K^+ homeostasis, and stimulate the activity of antioxidant enzymes such as superoxide dismutase (SOD) and catalase (CAT), as reported by Raliya *et al*. (2015) and Khalid *et al*. (2021). TiO_2 NPs enhanced photosynthesis and light absorption, despite the possibility of excessive ROS generation at high concentrations (Ali *et al*., 2021). According to El-Gazzar *et al*. (2020) and Farooq *et al*. (2022), Fe_3O_4 and MgO supported osmotic adjustment, redox regulation, enzyme activation, and chlorophyll synthesis, resulting in moderate improvements. The fact that untreated plants had the lowest TOL demonstrated the significance of nanoparticles in improving salt tolerance.

Yield stability index (YSI)

YSI indicated the nanoparticles' capacity to sustain production under salinity stress, although the differences were treatment-specific. ZnO and MgO NPs improved photosynthetic efficiency, osmolyte accumulation, chlorophyll synthesis, and antioxidant defence, resulting in the highest YSI values, as supported by previous studies (Ramesh *et al*., 2014; Ghasemi *et al*., 2020). Fe_3O_4 exhibited a smaller effect than TiO_2, presumably due to restricted uptake, whereas TiO_2 conferred moderate benefits. Our findings align with earlier research on nanoparticle-mediated salinity tolerance in legumes, where ZnO and MgO effectively enhanced physiological resilience and reduced yield losses under salt stress (Hussain *et al*., 2019; Salama *et al*., 2022).

Conclusion

Salinity had a significant impact on plant height and biomass accumulation, ultimately disrupting growth and yield. Foliar application of NPs effectively mitigated these effects and improved vegetative as well as reproductive functions under saline conditions. Among the treatments, ZnO nanoparticles performed better than MgO, suggesting that they may enhance plant tolerance to salinity. Based on these results, soybean yield can be maintained by using ZnO and MgO NPs as effective nano-agronomic treatments. Future studies should explore the physiological, biochemical, and molecular mechanisms underlying the beneficial and complementary effects of NPs in soybean cultivation under saline conditions.

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Conflict of Interest

The authors affirm that no financial or commercial relationships that might be construed as a potential conflict of interest existed during the course of the research.

Author Contributions

Supervision, conceptualization, writing – original draft, funding acquisition: Md. Abdul Mannan and Md. Abdullah Al Mamun; Investigation, Methodology, Data curation, writing: Most. Tanjina Akter; Data analysis, review, and editing: Masuma Akter.

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