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Impact of Salinity Stress and ZnO-NPs on Macro and Micronutrient Assimilation: Unraveling the Link between Environmental Factors and Nutrient Uptake

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ABSTRACT

The purpose of this experiment was to investigate the effects of salinity (NaCl) on the mineral composition and macro- and micronutrient contents of rice plants. The experiment was conducted at the Department of Biotechnology's experimental area in SVPUAT Meerut. Various salinity treatments were applied, including T0 (Control), T1 (60 mM NaCl), T2 (80 mM NaCl), T3 (100 mM NaCl), T4 (ZnO NPs 50 mg/L + 60 mM NaCl), T5 (ZnO NPs 50 mg/L + 80 mM NaCl), and T6 (ZnO NPs 50 mg/L + 100 mM NaCl). The results analysis revealed that the micro- and micronutrients in rice genotypes decreased compared to the control treatment. However, when 50 mg/L of ZnO-NPs were applied, the concentrations of both macro- and micronutrient contents in rice plants were found to increase. This is the most significant finding of this research.

Keywords: salinity stress, macronutrient, micronutrient, ZnO-NPs, rice

INTRODUCTION

The salinization of soils is a widely recognized issue that can be attributed to both human activities and climate change. This problem poses a significant threat to the production of high-quality agricultural goods (Van Zelm et al., 2020). The growing global population has resulted in increased agricultural demands, leading to greater water consumption, and straining the limits of this vital resource (Mahajan and Tuteja, 2005). Unfortunately, agricultural practices, including the use of fertilizers and inadequate irrigation systems, combined with rising sea levels, have contributed to deteriorating water quality and the development of saline soil conditions (Singh et al., 2021). The consequences of salinity stress on various aspects of plant growth and development are extensive and encompass seed germination, seedling growth, leaf size, shoot growth, shoot, and root lengths, shoot dry weight, shoot fresh weight, number of tillers per plant, flowering stage, spikelet number, percentage of sterile florets, nutrient content and overall productivity (Al-Tawaha et al. 2005; Al-Tawaha et al. 2013; Deinlein et al., 2014; Al-Tawaha et al. 2018; Al-Tawaha et al. 2021; Amanullah et al. 2021; Singh et al., 2022a). It is evident that salinity stress exerts detrimental effects on multiple facets of plant physiology, ultimately

compromising crop productivity (Tawaha 2005; Imran et al. 2020; Imran et al. 2021a, 2021b). Salinity stress disrupts the equilibrium of mineral nutrient uptake and distribution within plants. Saline conditions drastically change the environment of root aeration, osmotic potential of soil solution and normal equilibrium of the dissolved ions (Kumar and Sharma, 2020). The availability of most macronutrients and micronutrients to crop plants mainly depends upon the pH of the soil solution as well as the nature of binding sites on organic and inorganic particle surfaces. In saline and sodic soils, the solubility of macro (Ca) and micronutrients (Cu, Mn, Fe, Zn) is particularly low, and plants growing on such soils often experience deficiencies in these elements (Flowers and Colmer, 2015).

Nanoparticles (NPs) have emerged as potential nutrient sources, particularly for macro and micronutrients (Alam et al., 2022; Chhipa, 2017; Rostami Ajirloo and Amiri, 2022). The utilization of NPs for the controlled release of essential nutrients has been proposed as a potential solution to address soil contamination and low agronomic productivity (Raliya et al., 2016). Among various types of NPs, ZnO-NPs have gained significant attention and are widely utilized in diverse industrial applications (Sarraf et al., 2022). ZnO-NPs have also been suggested as an effective zinc source for plants, particularly when applied at lower levels, to meet their zinc requirements (Milani et al., 2015). Furthermore, studies have demonstrated that ZnO-NPs, at concentrations of 1∼20 ppm, promote the growth of mung beans and chickpeas (Mahajan et al., 2011). Additionally, ZnO-NPs have been found to enhance cotton growth and mitigate oxidative stress in plants, as evidenced by Venkatachalam et al. (2017). These findings collectively emphasize the potential of ZnO-NPs as a beneficial tool for enhancing plant growth by balancing the macro and micronutrient availability for plants and alleviating stress-related concerns (Singh et al., 2021).

Rice (*Oryza sativa* L.) serves as a vital staple crop, providing sustenance for over 50% of the global population (Ray et al., 2013). However, the detrimental impact of salinity on rice production is a major concern due to the crop's high sensitivity to saline conditions. Consequently, it is imperative to comprehensively characterize the physiological responses of rice to salinity stress in order to address this challenge and enhance productivity (Rajput et al., 2021). To achieve future improvements in rice cultivation, a deeper scientific understanding of nutrient assimilation is crucial, with a specific focus on rate of absorption or uptake under salinity stress conditions. This research should also encompass the examination of macro (Ca^{2+}) and micronutrient (Zn^{2+} Fe^{2+}, Cu^{2+} and Mn^{2+}) contents, elucidating their roles in rice growth and development in the presence of salinity stress. By acquiring a profound knowledge of root system architecture and the influence of salinity stress on nutrient uptake and distribution, we can pave the way for targeted approaches to improve rice cultivation, ensuring food security and sustainability for the growing global population.

MATERIAL AND METHOD

Plants material procurements

Nine-varieties of healthy rice seeds were collected from BEDF Meerut, India, and the Zonal Research Station Nagina, Bijnor, Uttar Pradesh, India (Table 1).

Table 1. Different rice genotypes their origin, pedigree, releasing year and date

S.NO	Rice genotypes	Origin	Pedigree	Notification No. & Date
1.	Panjab Basmati 3	PAU, India	-	3540(E) – 24.11.2016
2.	Pusa Basmati 1728	IARI, New Delhi, India	PB6/Pusa 1460	3540(E) – 24.11.2016
3.	Panjab Basmati 2	PAU, India	-	1708 (E) – 26.07.2012
4.	Pusa Basmati 1	IARI, New Delhi, India	Pusa150/Karnal Local	615 (E) – 06.11.1989
5.	Panjab Basmati 1	PAU, India	-	596 (E) – 13.08.1984
6.	Pusa Basmati 6	IARI, New Delhi, India	Pusa Basmati 1/Pusa 1121	733 (E) – 01.04.2010
7.	Vallabh Basmati 24	SVBPUA&T, India	-	268(E) – 28.01.2015
8.	Pusa Basmati 1718	IARI, New Delhi, India	PB1121/Pusa1460	2805(E) – 25.08.2017
9.	Pusa Basmati 1121	IARI, New Delhi, India	-	-

Plant pot culture

The study was conducted in pots (33 cm diameter × 23 cm depth) at the shelter house of the Department of Agriculture Biotechnology, S.V.P.U.A.&T., Modipuram, Meerut, U.P. The pots were filled with 8 kg of soil and 5 L of water, ensuring flooded watering conditions necessary for the growth and development of rice plants. Rice seedlings at the active tillering stage (30 days old) were exposed to different concentrations of sodium chloride (NaCl): 60 mM, 80 mM, and 100 mM. For the 60 mM, 80 mM, and 100 mM NaCl treatments, 45.71 g, 60.95 g, and 76.18 g of pure NaCl were dissolved in 1 L of water, respectively, and added to the pots according to the treatment plan. Not NaCl was added to the soil for the control treatment. To prevent osmotic shock to the plants, salt solutions were gradually applied in four steps. Additionally, a foliar application of ZnO-NPs (50 mg/L) was applied on a weekly basis starting from 5 days after the onset of salt stress. The experiment was organized in a Completely Randomized Design (CRD) with three replicates. Data collection for the different treatments involved uprooting the rice plants, along with their respective control plants, two weeks after the application of salt stress.

Treatments

The study conducted experiments using both pot plant culture systems, investigating the effects of different treatments involving sodium chloride (NaCl) and ZnO-NPs. The treatments were as follows: T0 (Control), T1 (60 mM NaCl), T2 (80 mM NaCl), T3 (100 mM NaCl), T4 (ZnO NPs 50 mg/L + 60 mM NaCl), T5 (ZnO NPs 50 mg/L + 80 mM NaCl), and T6 (ZnO NPs 50 mg/L + 100 mM NaCl). These treatments were applied to assess the impact of salinity stress on micronutrient contents in the plants. The study employed a concise experimental design to systematically analyze and compare plant responses under different stress conditions.

Nutrient assimilation or uptake analysis

Two weeks after the application of salt stress and foliar application of ZnO-NPs the plant samples were collected to measure the uptake of Zn^{2+} $Ca^{2+,}$ Fe^{2+}, Cu^{2+} and Mn^{2+} micronutrients concentrations in treated rice genotypes. The rice samples were dried in a forced draft oven at 65°C for 72 hours. After drying, the plant materials were collected for chemical analyses. Dried rice samples were first ground into a fine powder and weighed. Subsequently, 0.5 g of the ground samples were mixed with 10 mL of a 2:1 solution of nitric acid and perchloric acid for pre-digestion. The mixture was allowed to stand overnight for 24 hours. The flasks containing the mixture were then placed on a hot plate and heated until the orange fumes turned into white fumes, indicating complete digestion of the rice samples. To facilitate further filtration, 2–3 mL of deionized water were added to 50 mL glass volumetric flasks, and the remaining volume was filled with deionized water from 100 mL flasks. The resulting solution was filtered, and the filtrate was obtained for subsequent analysis. An atomic absorption spectrometer (GBC-SavantAA-01-1006-03, Mumbai, India) was utilized to analyze the filtered extract and determine the concentrations of Zn, Mn, Cu, and Fe (Abdelhamid et al., 2020). Ca^{2+} content in rice plant samples was analyzed by titration methods followed by Lee and Campbell (1969) protocol.

Statistical analysis

The statistical analysis were conducted using SPSS software version 16.0. One-way and two-way analysis of variance (ANOVA) were performed to evaluate the data, and each experiment was replicated three times. To identify significant differences among means, Duncan's test was employed with a significance level of $p \leq 0.01$.

RESULTS AND DISCUSSION

Under salinity stress, the Zn^{2+}, Ca^{2+}, Fe^{2+}, Cu^{2+} and Mn^{2+} of plants is reduced (Taffouo et al., 2009). In current study different rice genotypes were exposed to various concentrations of NaCl (60 mM, 80 mM, and 100 mM) which resulted in decreased plant Zn^{2+}, Ca^{2+}, Fe^{2+}, Cu^{2+}, and Mn^{2+} when compared to control plants. The most significant reduction was observed in Pusa Basmati, followed by Panjab Basmati 3, Pusa Basmati 1728, Panjab Basmati 2, Pusa Basmati 1121, Panjab Basmati 1, Pusa Basmati 6, Vallabh Basmati 24, and Pusa Basmati 1718 for T1, T2, and T3 treatments compared to their respective controls (Table 2-6). However, the application of ZnO-NPs in treatments T4, T5, and T5 resulted in less reduction in Zn^{2+}, Ca^{2+}, Fe^{2+}, Cu^{2+}, Mn^{2+} for all the genotypes including Pusa Basmati 1, Panjab Basmati 3, Pusa Basmati 1728,

Panjab Basmati 2, Pusa Basmati 1121, Panjab Basmati 1, Pusa Basmati 6, Vallabh Basmati 24, and Pusa Basmati 1718 when compared to both NaCl and controls (Tables 1–5).

The results from Table 2 indicate that the concentration of Zn ions decreased in all rice genotypes for treatments T1, T2, and T3 under saline conditions. However, the reduction was more pronounced in Pusa Basmati 1 compared to its control. On the other hand, the foliar application of ZnO-NPs (T4, T5, and T6) resulted in an enhancement of Zn content under saline conditions in all rice genotypes. However, a significant improvement was not observed specifically in Pusa Basmati 1. Similarly the findings of Mogazy and Hanafy (2022) demonstrated that the application of 150 mM NaCl resulted in a reduction of Zn contents in *Vicia faba* plants. However, foliar application of ZnO-NPs at a concentration of 50 mg L^{-1} showed an improvement in Zn contents in *Vicia faba* plants under salinity stress. Zn can be applied directly to the soil in various organic and inorganic forms. Among the inorganic sources, $ZnSO_4$ is commonly used due to its high solubility and cost-effectiveness. Other forms of Zn that can be applied to soils include ZnO, Zn-EDTA, and Zn-oxysulfide (Cakmak, 2008). The utilization of synthesized ZnO-NPs can offer benefits in terms of enhancing fertilizer use efficiency and potentially having a positive impact on the environment. For instance, the use of NPs allows for controlled release of nutrients according to the specific requirements of crops while minimizing nutrient interaction with microorganisms, water, and soil, which can lead to nutrient immobilization (Monreal et al., 2015). This controlled formulation of ZnO-NPs can contribute to improved nutrient availability under salinity stress (Alabdallah and Alzahrani, 2020). Singh et al. (2022a) experiment suggested that application of 50 mg/L ZnO-NPs can enhanced the Zn content in rice genotypes seedlings under saline environment. Similarly Srivastav et al. (2021) was observed 100 mg/L of ZnO-NPs can enhanced the Zn content in wheat and maize. All these findings support our result that the application of ZnO-NPs can enhance the zinc content under salinity stress, which helps in plant growth and development.

The results from Table 3 indicate that the application of ZnO-NPs can enhance the Ca^{2+} content under salinity stress, thereby contributing to plant growth and development. Specifically, the application of 50 mg/L ZnO-NPs resulted in enhanced Ca^{2+} contents in all the genotypes, including Pusa Basmati 1, Panjab Basmati 3, Pusa Basmati 1728, Panjab Basmati 2, Pusa Basmati 1121, Panjab Basmati 1, Pusa Basmati 6, Vallabh Basmati 24, and Pusa Basmati 1718, when compared to both NaCl and control conditions. However, a comparatively lesser improvement was observed in Pusa Basmati 1 under saline conditions. Ca is crucial for maintaining cellular functions and is a constituent of plant tissues (Elmer et al., 2007). Additionally, calcium ions play a regulatory role in fruit ripening (Singh et al., 2009). Unlike some other elements, calcium is immobile within plants, making direct contact with calcium a more efficient means of enhancing its content (Manganaris et al., 2005). The experiment conducted by Lalarukh et al. (2022) observed that the application of 50 mg/L ZnO-NPs enhanced Ca^{2+} levels in wheat under salinity stress, which supports our findings. Salt toxicity results in the hyperaccumulation of NaCl, which inhibits Ca^{2+} uptake and leads to ionic imbalance. However, the application of 50 mg/L ZnO-NPs has been shown to enhance Ca^{2+} uptake in *Linum usitatissimum* under saline conditions (Singh et al., 2021). This finding supports our results, suggesting that the application of ZnO-NPs can enhance Ca^{2+} levels in rice genotypes when subjected to salinity stress.

Data presented in Table 4 showed the salinity stress reduced the Fe contents in rice genotypes. Under salinity stress, the Fe^{2+} contents in plants are reduced, as observed in several research articles (Taffouo et al., 2009). Salinity-induced reduction in Fe^{2+} uptake and availability negatively impact plant growth and development. This decrease in Fe^{2+} content can lead to various physiological and metabolic imbalances, affecting vital processes such as photosynthesis, respiration, and enzyme activities. Singh et al. (2021) observed that the application of ZnO-NPs at a concentration of 50 mg/L has the potential to improve Fe^{2+} nutrient absorption in plants. ZnO-NPs facilitate the transfer of Fe^{2+} ions to different parts of the plant through xylem and phloem tissues. This enhanced Fe^{2} transport plays a vital role in reducing oxidative stress caused by salinity stress. The improved uptake and distribution of Fe^{2+} elements, facilitated by ZnO-NPs, contribute to the alleviation of oxidative damage and overall enhancement of plant health under salinity stress. Similarly, in our study, we observed that the application of 50 mg/L of ZnO-NPs upregulated the concentration of Fe^{2+} in rice genotypes under salinity stress, as shown in Table 4. The presence of ZnO-NPs enhanced the availability and uptake of Fe^{2+} by the plants, mitigating the negative effects of salinity

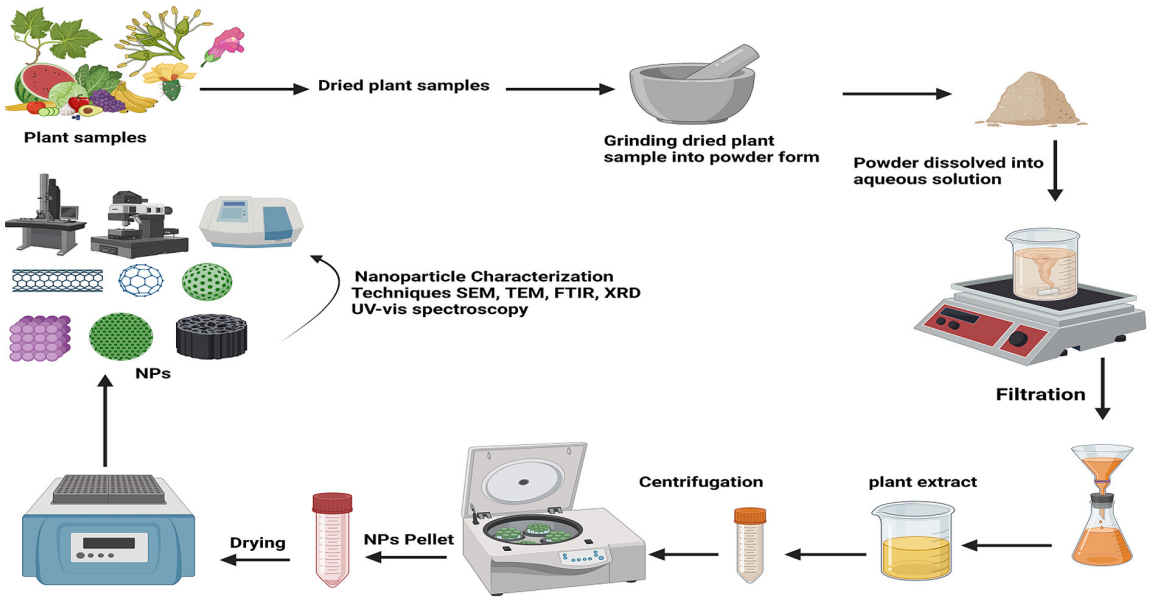

Figure 1. The process for the analysis of macro and micronutrients from the initial stage of pot filling to the analysis stage involves the digestion of rice samples, followed by AAS analysis of Zn^{2+}, Fe^{2+}, Cu^{2+}, and Mn^{2+} ions. Additionally, a simple titration method is used to analyze Ca^{2+} ions in the rice samples

stress on Fe^{2+} levels. These findings highlight the potential of ZnO-NPs as a promising strategy to improve Fe^{2+} absorption and alleviate Fe deficiency in rice plants facing salinity stress (Abdel Latef et al., 2017; Akter and Oue, 2018; Grotz and Guerinot, 2006; Priyanka et al., 2021)

Copper (Cu^{2+}) and manganese (Mn^{2+}) are essential micronutrients required for proper plant growth and development (Martens and Lindsay, 2018). They act as cofactors for enzymes involved in numerous physiological processes, including electron transport, photosynthesis, lignin biosynthesis, and antioxidant defense mechanisms (Taffouo et al., 2009). However, salinity stress poses significant challenges to the uptake, transport, and utilization of Cu^{2+} and Mn^{2+} in plants, leading to disruptions in their vital functions. Salinity stress significantly affects the availability and utilization of Cu^{2+} and Mn^{2+} in plants. The presence of high salt levels in the soil alters root permeability and disrupts ion channels, leading to reduced uptake and transport of Cu^{2+} and Mn^{2+} into the plant (Table 5 and 6) (Kabir et al., 2010). Salinity-induced competition among various ions further hampers the availability and absorption of Cu^{2+} and Mn^{2+} (Bekmirzaev et al., 2020). Similarly in our finding the salt stress recued the Cu^{2+} and Mn^{2+} content in all rice genotypes (Table 5 and 6). Excessive accumulation of sodium ions (Na^{+}) under salinity stress can also lead to antagonistic interactions with Cu^{2+} and Mn^{2+}, impairing their uptake and translocation within the plant. Additionally, salinity stress-induced oxidative stress can negatively impact the activity and efficiency of Cu^{2+} and Mn^{2+}dependent enzymes, resulting in functional impairments and disruptions in plant metabolism (Bhatla and Lal, 2018). ZnO-NPs have been reported to enhance Cu^{2+} uptake in plants under salinity stress (Mogazy and Hanafy, 2022). The ZnO-NPs facilitate the transport and entry of Cu^{2+} into plant roots through various mechanisms (Adil et al., 2022). ZnO-NPs enhance root permeability, ensuring efficient Cu^{2+} uptake and transport to aerial plant parts (Rakgotho et al., 2022; Singh et al., 2022b). Additionally, ZnO-NPs influence ion channels, promoting the uptake of Cu^{2+} ions in the presence of high salinity levels (Sharifan et al., 2020). These interactions between ZnO-NPs and Cu^{2+}contribute to the improved Cu^{2+}uptake, addressing the negative effects of salinity stress (Akter and Oue, 2018). Our finding shows similar result that application of 50 mg/L of ZnO-NPs can enhanced $Cu^{2+}$and Mn^{2+} content in rice genotypes (Table 4 and 5). The mechanisms underlying the enhanced Cu^{2+} and Mn^{2+} uptake by ZnO-NPs is multifaceted. ZnO-NPs enhance the root surface area, providing more sites for Cu^{2+} and Mn^{2+} adsorption (Abuhatab et al., 2020; Singh et al., 2022b). These nanoparticles also stimulate root hair development, increasing nutrient absorption capacity. Furthermore, ZnO-NPs influence ion transporters and channels, facilitating the movement of Cu^{2+} and Mn^{2+} across cell membranes

Table 2. Effect of salinity stress and ZnO-NPs on Zn^{2+} content (mg/ kg) DW of different varieties of rice. Error bars show the least significant value (LSD) at $p \leq 0.01$ among the treatments

Varieties	Treatments						
	T0	T1	T2	T3	T4	T5	T6
Panjab Basmati 3	78.77±0.64	59.33±1.44	45.33±1.26	33.45±0.49	145.33±2.10	125.77±1.81	109.66±3.04
Pusa Basmati 1728	74.77±1.81	61.33±0.50	49.22±1.76	35.33±0.51	155.33±4.31	132.66±3.22	120.88±1.74
Panjab Basmati 2	75.80±2.71	55.44±0.45	46.22±1.12	33.22±0.92	140.44±2.03	115.33±4.13	102.55±0.83
Pusa Basmati 1121	78.91±1.91	62.31±0.90	47.69±0.39	35.71±0.87	160.22±2.32	145.77±5.22	125.88±1.02
Pusa Basmati 1	75.80±1.84	52.33±1.45	40.11±0.58	30.22±1.08	127.75±1.03	100.79±1.46	89.99±2.49
Panjab Basmati 1	81.90±1.18	50.22±0.40	42.22±0.61	31.22±0.25	137.44±3.81	118.44±1.71	104.33±2.53
Pusa basmati 6	79.11±0.64	62.56±0.90	48.22±0.39	35.91±1.29	155.91±2.25	145.88±3.54	120.88±0.98
Vallabh Basmati 24	80.22±2.87	63.66±0.92	50.22±1.39	36.33±0.88	167.22±1.35	155.77±3.78	137.89±3.82
Pusa Basmati 1718	79.92±2.86	59.22±1.44	49.22±0.40	34.33±0.83	160.91±2.32	141.77±3.44	125.71±4.50

Table 3. Effect of salinity stress and ZnO-NPs on Ca^{2+} content (mg/ kg) DW of different varieties of rice. Error bars show the least significant value (LSD) at $p \leq 0.01$ among the treatments

Varieties	Treatments						
	T0	T1	T2	T3	T4	T5	T6
Panjab Basmati 3	16.44±0.24	6.44±0.05	4.40±0.10	3.11±0.05	10.25±0.15	9.11±0.25	7.15±0.17
Pusa Basmati 1728	19.33±0.16	6.99±0.25	5.32±0.08	3.98±0.11	14.65±0.36	13.12±0.10	11.11±0.27
Panjab Basmati 2	20.33±0.29	5.22±0.19	4.55±0.04	3.03±0.08	15.35±0.43	14.05±0.20	13.11±0.47
Pusa Basmati 1121	19.66±0.16	6.23±0.15	5.02±0.18	4.01±0.04	14.25±0.35	13.41±0.20	10.11±0.36
Pusa Basmati 1	18.99±0.16	5.060.12	3.31±0.09	2.78±0.04	13.98±0.50	10.15±0.28	8.71±0.21
Panjab Basmati 1	19.45±0.54	5.70±0.20	3.22±0.08	2.99±0.11	15.74±0.38	13.11±0.36	11.41±0.09
Pusa Basmati 6	19.99±0.72	6.79±0.19	4.52±0.16	3.69±0.05	14.98±0.36	11.51±0.09	10.41±0.38
Vallabh Basmati 24	20.33±0.29	7.54±0.21	4.88±0.12	4.01±0.04	16.84±0.24	14.41±0.12	12.41±0.30
Pusa Basmati 1718	18.30±0.27	6.88±0.06	3.89±0.14	3.11±0.02	12.41±0.35	10.11±0.08	8.41±0.12

Table 4. Effect of salinity stress and ZnO-NPs on Fe^{2+} content (mg/ kg) DW of different varieties of rice. Error bars show the least significant value (LSD) at $p \leq 0.01$ among the treatments

Varieties	Treatments						
	T0	T1	T2	T3	T4	T5	T6
Panjab Basmati 3	178.77±4.34	69.33±1.92	45.83±0.66	34.50±0.28	142.13±5.09	128.57±1.85	110.46±3.06
Pusa Basmati 1728	174.74±4.24	81.33±0.66	50.22±1.80	36.23±0.53	150.43±3.65	135.66±1.10	121.58±3.37
Panjab Basmati 2	175.81±2.54	55.84±2.00	47.32±0.38	32.52±0.79	142.24±2.06	117.63±4.21	106.61±0.86
Pusa Basmati 1121	178.21±4.32	72.31±2.00	48.59±0.39	36.81±0.90	155.23±4.30	146.67±2.12	134.78±4.83
Pusa Basmati 1	175.40±1.42	50.33±1.22	41.51±0.60	30.01±1.07	125.75±1.02	101.69±1.47	85.69±2.08
Panjab Basmati 1	181.39±2.62	52.29±0.42	42.22±1.17	31.62±1.13	134.34±3.26	116.34±1.68	106.63±2.59
Pusa Basmati 6	179.01±6.41	72.56±1.05	48.22±1.73	37.91±0.55	159.91±4.43	143.88±3.49	125.68±1.02
Vallabh Basmati 24	180.52±2.60	93.66±1.35	50.22±1.22	38.33±0.31	170.22±6.09	155.67±1.26	139.79±3.39
Pusa Basmati 1718	179.52±2.59	79.32±1.92	49.22±1.76	35.33±0.86	161.91±2.34	140.67±3.41	128.81±1.86

(Sharifan et al., 2020). The presence of ZnO-NPs in the root environment induces physiological and biochemical changes that enhance Cu^{2+} and Mn^{2+} uptake and translocation within the plant.

CONCLUSIONS

The study found that salinity stress had a negative impact on the nutrient levels of rice plants when compared to control plants. However, the use of ZnO-NPs not only counteracted the negative effects of salinity stress but also significantly improved the levels of various nutrients such as Zn^{2+}, Ca^{2+}, Fe^{2+}, Cu^{2+} and Mn^{2+} in rice genotypes Pusa Basmati 1, Panjab Basmati 3, Pusa Basmati 1728, Panjab Basmati 2, Pusa Basmati 1121, Panjab Basmati 1, Pusa Basmati 6, Vallabh Basmati 24, and Pusa Basmati 1718. However, it was observed that Pusa Basmati 1 did not show as much improvement after the

Table 5. Effect of salinity stress and ZnO-NPs on Cu^{2+} content (mg/ kg) DW of different varieties of rice. Error bars show the least significant value (LSD) at $p \leq 0.01$ among the treatments

Varieties	Treatments						
	T0	T1	T2	T3	T4	T5	T6
Panjab Basmati 3	6.14±0.05	4.14±0.10	3.32±0.09	2.71±0.10	5.88±0.09	4.51±0.13	3.80±0.09
Pusa Basmati 1728	6.49±0.05	5.12±0.19	4.08±0.06	2.81±0.07	5.31±0.04	4.50±0.16	3.66±0.09
Panjab Basmati 2	5.72±0.16	4.850.07	3.10±0.11	2.78±0.02	5.18±0.13	4.02±0.06	3.65±0.13
Pusa Basmati 1121	6.53±0.05	5.12±0.13	4.31±0.06	2.91±0.02	5.45±0.13	4.55±0.13	3.88±0.06
Pusa Basmati 1	5.160.19	3.41±0.03	2.98±0.08	2.30±0.04	4.45±0.16	3.69±0.09	3.12±0.02
Panjab Basmati 1	5.66±0.14	3.88±0.06	3.04±0.08	2.88±0.04	5.02±0.04	4.03±0.10	3.37±0.03
Pusa Basmati 6	6.89±0.10	4.62±0.11	3.62±0.05	2.89±0.08	5.96±0.14	4.65±0.04	3.92±0.06
Vallabh Basmati 24	7.74±0.11	4.91±0.12	4.06±0.04	3.11±0.11	6.01±0.09	5.03±0.18	4.01±0.04
Pusa Basmati 1718	6.91±0.10	3.91±0.03	3.18±0.05	2.98±0.02	5.78±0.14	4.43±0.04	3.55±0.10

Table 6. Effect of salinity stress and ZnO-NPs on Mn^{2+} content (mg/ kg) DW of different varieties of rice. Error bars show the least significant value (LSD) at $p \leq 0.01$ among the treatments

Varieties	Treatments						
	T0	T1	T2	T3	T4	T5	T6
Panjab Basmati 3	180.77±6.47	79.33±0.64	55.83±1.35	44.50±0.64	148.33±4.11	130.17±3.16	109.56±0.88
Pusa Basmati 1728	184.64±6.61	83.43±1.21	51.72±1.25	37.43±0.30	155.43±5.57	138.46±2.00	124.68±1.01
Panjab Basmati 2	185.31±4.49	53.94±1.50	46.62±0.68	33.62±1.20	144.54±1.17	118.53±2.88	107.81±1.56
Pusa Basmati 1121	188.11±6.73	74.41±0.60	49.49±0.72	39.91±0.58	157.13±1.27	147.87±3.59	138.88±3.85
Pusa Basmati 1	179.78±2.59	52.33±1.87	44.51±0.36	31.06±0.75	129.75±1.87	105.69±0.85	91.69±3.28
Panjab Basmati 1	185.79±1.50	55.29±0.80	44.22±0.36	32.62±0.91	138.64±4.97	118.64±0.96	109.53±1.58
Pusa Basmati 6	182.08±5.05	74.56±0.60	51.22±1.42	39.91±0.97	160.91±1.30	145.88±2.11	128.68±1.86
Vallabh Basmati 24	188.52±4.57	95.61±0.77	51.27±1.84	39.63±0.57	171.22±4.75	165.67±2.39	141.79±5.08
Pusa Basmati 1718	181.52±4.40	79.22±1.14	51.22±1.42	37.13±0.54	160.11±1.29	141.67±2.04	130.81±3.17

application of 50 mg/L of ZnO-NPs compared to the other rice genotypes. In conclusion, the study suggests that implementing 50 mg/L ZnO-NPs can alleviated the negative effect on nutrients assimilation or uptake processes. In the future, the utilization of ZnO-NPs, in conjunction with other clean and environmentally safe techniques, alongside conventional methods, could potentially alleviate the detrimental impacts of salinity stress and aid in nutrient management. This comprehensive approach has the capacity to enhance soil sustainability in irrigated areas and improve the viability of rice as a food crop.

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