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Impact of Zinc Oxide Nanoparticles and Organic Manures on Potato Yield and Tuber Quality under Saline Conditions

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Abstract

Soil salinity is a major abiotic constraint limiting potato (Solanum tuberosum L.) productivity and tuber quality, particularly in arid and semi-arid regions. Salinity induces osmotic stress, ionic toxicity, and oxidative damage, resulting in reduced photosynthesis, impaired nutrient uptake, and significant yield losses. The present study synthesizes current advances on the integrated use of zinc oxide nanoparticles (ZnO NPs) and organic manures as a sustainable strategy to mitigate salinity stress in potato cultivation. ZnO nanoparticles enhance plant tolerance by improving zinc bioavailability, sustaining photosynthetic efficiency, activating antioxidant defense systems, and regulating stress-responsive hormonal and molecular pathways. In parallel, organic manures improve soil physical structure, increase cation exchange capacity, reduce sodium toxicity, and stimulate beneficial soil microbial communities. The synergistic application of ZnO NPs and organic amendments significantly improves plant growth, tuber yield components, starch accumulation, antioxidant profiles, and zinc biofortification under saline conditions. Moreover, this integrated nano-organic approach contributes to soil health restoration while minimizing environmental risks associated with excessive chemical fertilizer use. Overall, the combined use of ZnO nanoparticles and organic manures represents a promising, eco-friendly strategy for enhancing potato productivity, tuber quality, and nutritional value in salt-affected soils, offering practical implications for climate-resilient and sustainable agriculture.

Keywords: Potato; Salinity stress; Zinc oxide nanoparticles; Organic manures; Tuber quality; Antioxidant defense; Soil remediation; Zinc biofortification

1. Introduction

The global agricultural sector is currently confronted with a formidable challenge: the necessity to increase food production for an ever-expanding population while the available arable land is increasingly compromised by environmental stressors. Among these stressors, soil salinization has emerged as a critical constraint to sustainable crop production, particularly in arid and semi-arid regions where irrigation with brackish water and high evapotranspiration rates lead to the accumulation of soluble salts (Arora et al., 2024).

The potato (*Solanum tuberosum* L.) occupies a strategic position in global food security as the fourth most important staple food crop, yet it is classified as moderately sensitive to salinity, with significant yield losses occurring even at relatively low levels of electrical conductivity (Shah et al., 2022). Salinity disrupts the osmotic balance of the plant, induces oxidative stress, and leads to specific ion toxicities that interfere with tuber initiation and starch accumulation (Alghamdi et al., 2022). Projections indicate that in countries like India, the salt-affected area currently encompassing approximately 6.73 million hectares could expand to 16.2 million hectares by 2050 if mitigation strategies are not implemented (Seleiman et al., 2023).

Consequently, researchers have turned to the integration of nanotechnology and organic soil amendments as a dual-pronged approach to alleviate the deleterious impacts of salinity. Zinc oxide nanoparticles (ZnO NPs) offer a high surface-area-to-volume ratio, facilitating better absorption and acting as a precursor to essential enzymatic activities that neutralize reactive oxygen species (Zaman et al., 2024). When combined with organic manures, which improve soil structure and increase the cation exchange capacity, these nanoparticles can effectively reduce the uptake of sodium ions (Ahmad et al., 2025). This report examines the mechanistic roles of ZnO NPs and organic manures in enhancing potato productivity and tuber quality within saline ecosystems.

2. The Physiological and Biochemical Pathophysiology of Salinity in Potato

Salinity stress in potato plants is not a singular event but a complex sequence of osmotic, ionic, and oxidative stresses that disrupt the plant's life cycle from emergence to tuber maturation (Alghamdi et al., 2022). The initial phase of salt stress is primarily osmotic, occurring almost immediately as the concentration of Na and Cl ions increases in the rhizosphere. This increase in the external osmotic pressure reduces the soil water potential, making it energetically difficult for roots to extract moisture, which effectively induces a state of physiological drought (Seleiman, Ahmad, et al., 2023).

2.1. Osmotic Stress and Vegetative Inhibition

The immediate consequence of this osmotic imbalance is a reduction in leaf expansion and a decrease in the number of leaves and branches (Seleiman, Al-Selwey, et al., 2023). Quantitative assessments have shown that salt stress can cause a mean reduction of 14.49% in plant height and 8.88% in stem numbers, significantly limiting the photosynthetic surface area (Shah et al., 2022).

Under more severe conditions (120 mM NaCl), plant height has been observed to drop significantly in in-vitro studies, reflecting the metabolic cost of survival over growth (Zaman et al., 2024). This stunting is a direct result of restricted cell division and elongation, as the plant prioritizes the accumulation of compatible solutes like proline over biomass accumulation (Ibrahim et al., 2023). Proline acts as a vital osmoprotectant, helping the plant maintain turgor pressure and stabilizing proteins and membranes against the dehydrating effects of salt, though its synthesis requires high levels of metabolic energy that would otherwise support tuber development (Hassan et al., 2024).

Table 1: Physiological and Yield Impacts of Different Salinity Levels on Potato

Salinity Level (NaCl Concentration)	**Impact on Plant Height (% Reduction)**	**Impact on Tuber Yield (% Reduction)**	**Physiological Marker Change**
50 mM	10–15%	~38%	Moderate Proline Increase (Alghamdi et al., 2022; Shah et al., 2022)
100 mM	25–35%	~50%	High MDA & ROS Accumulation (Alghamdi et al., 2022; Shah et al., 2022)
120 mM	>75%	>60%	Severe Membrane Rupture (Alghamdi et al., 2022)

2.2. Ionic Toxicity and Nutrient Homeostasis

As the duration of exposure increases, the second phase of salinity stress ionic toxicity becomes predominant. Sodium (Na^+) and Chloride (Cl^-) ions accumulate in the older leaves, leading to chlorosis, necrosis, and premature senescence (Alghamdi et al., 2022). The accumulation of Na^+ is particularly damaging because it competitively inhibits the uptake of potassium (K^+), a critical element for over 60 enzymatic reactions, stomatal regulation, and the translocation of carbohydrates (Shah et al., 2022).

A sharp decline in the K^+/Na^+ ratio is a hallmark of salt sensitivity in potatoes, as K^+ deficiency impairs the plant's ability to regulate its internal water status and maintain photosynthetic efficiency (Ahmad et al., 2025). This imbalance often leads to the displacement of calcium (Ca^{2+}) from cell membranes, further compromising structural integrity and signaling pathways (Zaman et al., 2024).

2.3. Ultrastructural and Oxidative Damage

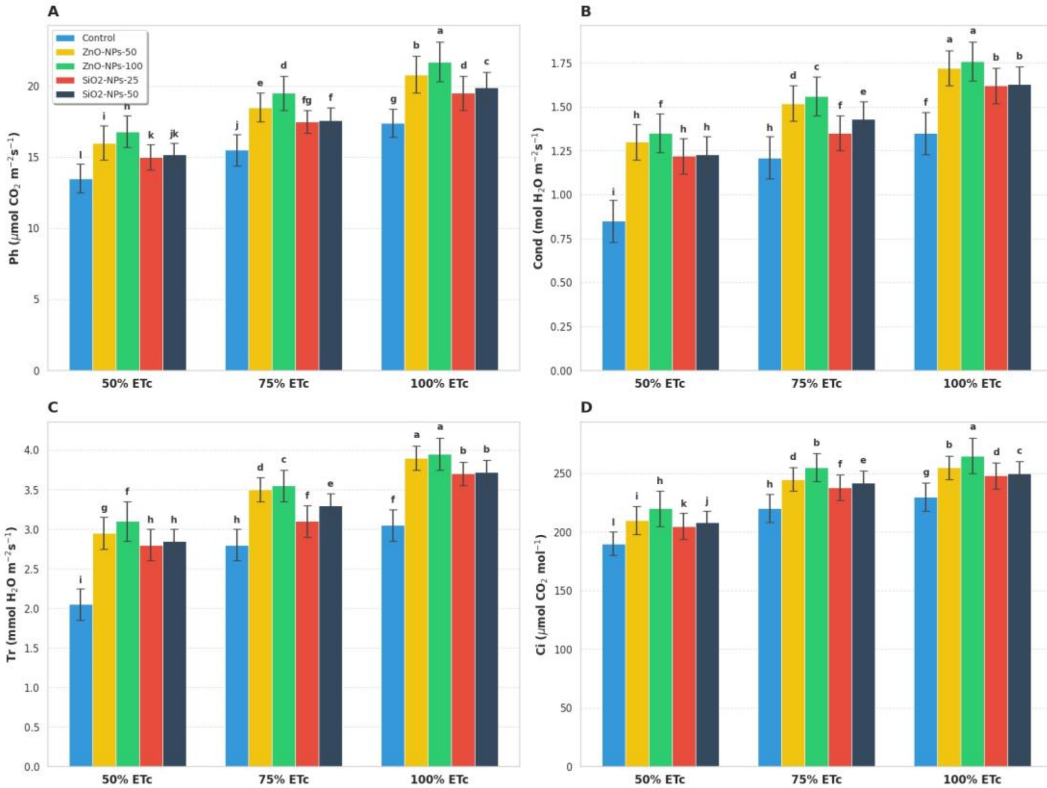
At the cellular level, high salinity induces significant ultrastructural changes. Research using test-tube plantlets has demonstrated that under 200 mM NaCl, chloroplast numbers decrease, intercellular spaces shrink, and cell walls thicken or eventually rupture (Alghamdi et al., 2022). The thylakoid membranes within the chloroplasts are particularly susceptible to degradation, which directly hampers the light-dependent reactions of photosynthesis (Ibrahim et al., 2023).

This structural decay is largely driven by the overproduction of reactive oxygen species (ROS), such as singlet oxygen, superoxide radicals, and hydroxyl radicals (Soliman et al., 2025). These ROS molecules cause lipid peroxidation of the cell membranes, leading to the accumulation of malondialdehyde (MDA) and a reduction in the membrane stability index (MSI) (Seleiman, Ahmad, et al., 2023). Failure to neutralize these radicals leads to programmed cell death and significant reductions in tuber dry matter accumulation (Hassan et al., 2024).

3. Mechanistic Role of Zinc Oxide Nanoparticles in Salinity Mitigation

The application of nanotechnology, specifically zinc oxide nanoparticles (ZnO NPs), has emerged as a transformative approach to bolstering potato resilience. Unlike bulk zinc fertilizers such as zinc sulfate ($ZnSO_4$), ZnO NPs possess unique physical and chemical properties, including a high surface-area-to-volume ratio and superior reactivity, which allow them to interact more efficiently with plant cellular structures (Nazir et al., 2024).

Figure 1. Interaction effects of water deficit (ETc) and exogenous nanoparticles (NPs) treatments on leaf gas exchange of potato; photosynthesis rate (A), stomatal conductance (B), transpiration rate (C) and intercellular CO_2 concentration (D). Al-Selwey et al., 2023)



3.1. Modulation of Photosynthetic and Metabolic Activity

ZnO NPs act as potent modulators of the plant's photosynthetic apparatus. Zinc is an essential cofactor for the enzyme carbonic anhydrase, which facilitates the reversible hydration of CO2 for the Calvin cycle (Mahmoud et al., 2020). By enhancing the bioavailability of zinc, ZnO NPs help maintain higher chlorophyll a and b levels and carotenoid content, even under salt-induced chlorosis (Arora et al., 2024). Studies on other crops have shown that ZnO NPs can improve chlorophyll content by up to 53% and relative water content (RWC) by 46% under stress (Rashwan & El-Sherpiny, 2023). In potatoes, foliar application of 50 to 100 mg/L ZnO NPs has been found to maintain stomatal structure and prevent deformation, thereby sustaining gas exchange and the net photosynthesis rate (Pn) (Seleiman, Al-Selwey, et al., 2023).

3.2. Activation of the Antioxidant Defense Network

A primary mechanism through which ZnO NPs mitigate salinity is the upregulation of the antioxidant defense system. ZnO NPs stimulate the activity of key enzymatic antioxidants, including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX) (Seleiman, Ahmad, et al., 2023).

The assessment of SOD activity is often conducted using established photochemical methods that identify the enzyme's role in inhibiting the photoreduction of nitroblue tetrazolium. For example, ZnO NP treatments have been shown to increase CAT activity significantly in stressed plants, which aids in the rapid detoxification of H2O2 into water and oxygen (Beyer & Fridovich, 1987).

This targeted scavenging of ROS prevents the irreversible oxidative damage to membrane lipids, significantly reducing MDA levels and preserving the integrity of the cellular environment (Seleiman, Ahmad, et al., 2023).

3.3. Hormonal and Molecular Signaling

ZnO NPs also function as molecular regulators by influencing the biosynthesis and signaling pathways of phytohormones. They have been observed to increase the levels of indole-3-acetic acid (IAA) and gibberellic acid (GA3), which promote root proliferation and stem elongation, thereby offsetting the growth-stunting effects of NaCl (Alghamdi et al., 2022).

Furthermore, ZnO NPs can modulate the expression of stress-responsive transcription factors, such as WRKY, bZIP, and NAC, which are responsible for activating genes involved in osmotic adjustment and ionic balance (Mahmoud et al., 2020). In some instances, ZnO NPs have been found to induce the accumulation of abscisic acid (ABA) and the expression of ABA-dependent genes like RD29A and NCED3, which are critical for the plant's adaptive response to the initial osmotic shock of salinity (Seleiman, Ahmad, et al., 2023).

4. Organic Manures as Agents of Soil Remediation

While ZnO NPs address the plant's internal response to stress, organic manures including farmyard manure (FYM), various composts, and vermicompost remediate the external soil environment. The strategic balancing of chemical fertilizer use with organic manure is vital for maintaining sustainable crop production in modern agriculture (Sindhushree et al., 2025). These amendments are crucial for restoring the fertility and physical integrity of salt-affected soils (Arora et al., 2024).

4.1. Physical Amelioration and Desalinization

Saline soils often suffer from poor physical structure, characterized by high bulk density and low porosity, which leads to poor drainage and the further accumulation of salts. The incorporation of organic matter facilitates the formation of stable soil aggregates through the action of microbial mucilage and fungal hyphae (El-Ghamry et al., 2024).

This improvement in soil structure increases hydraulic conductivity and enhances the infiltration of water, which allows for the leaching of excess Na+ and Cl- ions from the root zone to deeper soil layers (Arora et al., 2024). Specifically, planting green manure crops has been shown to significantly reduce soil bulk density and increase soil porosity, creating a more hospitable environment for potato roots (El-Ghamry et al., 2024).

4.2. Chemical Buffering and Cation Exchange

Organic manures significantly increase the soil's cation exchange capacity (CEC) by adding stable humus, which provides numerous negatively charged sites for the adsorption of essential cations like Ca2+, Mg2+, and K+ (El-Ghamry et al., 2024).

This process is vital in saline-sodic soils because the humic substances can sequester Na+ ions, reducing the exchangeable sodium percentage (ESP) and mitigating ion toxicity (Ahmad et al., 2025). Furthermore, the decomposition of organic matter releases CO2 and organic acids, which react with soil carbonates to form more soluble salts that can be leached, while simultaneously lowering the soil pH and increasing the availability of phosphorus and micronutrients (El-Ghamry et al., 2024).

4.3. Revitalization of the Soil Microbiome

Salinity stress typically exerts a strong selective pressure on the soil microbiome, reducing microbial biomass and inhibiting enzyme activities like urease and phosphatase (Arora et al., 2024). Amending soil with organic fertilizers has been shown to increase bacterial and fungal diversity, promoting the growth of salt-tolerant beneficial taxa (Sindhushree et al., 2025). These microorganisms play a synergistic role by fixing atmospheric nitrogen, solubilizing phosphorus, and producing growth-promoting substances that further assist the potato plant in resisting salt stress (El-Ghamry et al., 2024).

Table 2: Ameliorative Mechanisms of Organic Manures on Soil Properties under Salinity

Soil Property	**Effect of Salinity (Untreated)**	**Effect of Organic Manure Application**	**Ameliorative Mechanism**
Bulk Density	High (Compacted)	Reduced	Improved Aggregation (El-Ghamry et al., 2024)
Electrical Conductivity (EC)	High (>4 dS m-1)	Decreased	Leaching of Soluble Salts (El-Ghamry et al., 2024)
pH	High (Alkaline)	Stabilized/Lowered	Organic Acid Release (El-Ghamry et al., 2024)
Microbial Biomass	Very Low	Significantly Increased	Energy Source (Carbon) (Arora et al., 2024; El-Ghamry et al., 2024)

5. Synergistic Impacts on Potato Yield and Productivity

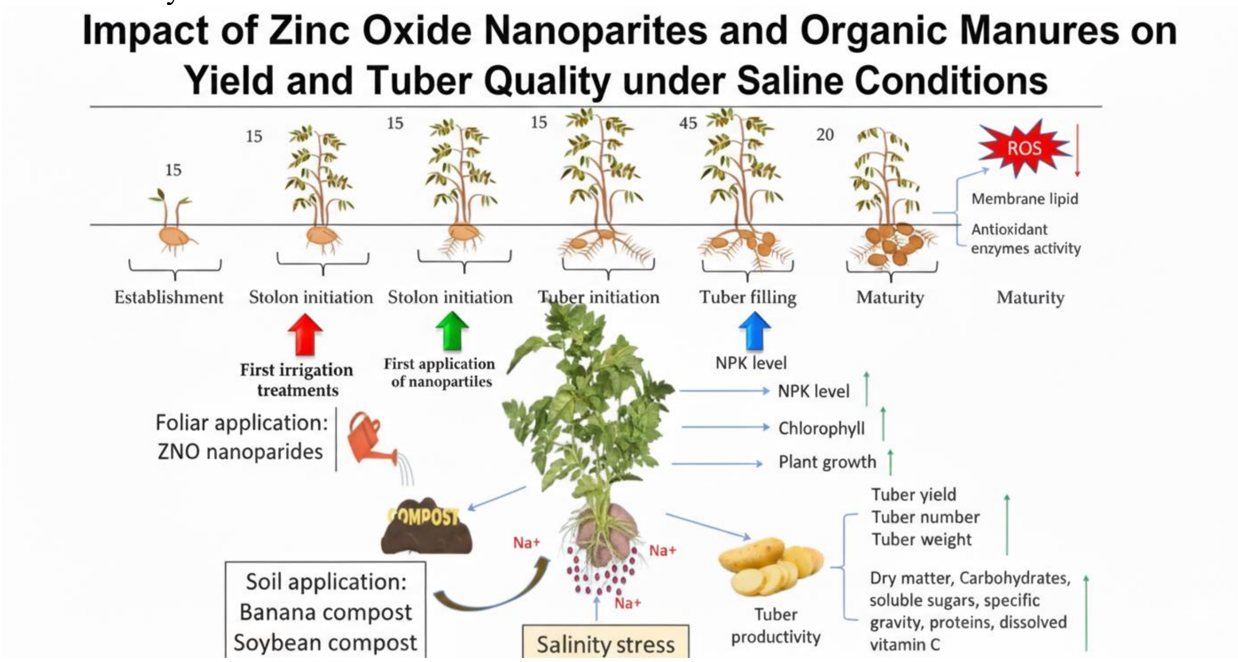
The most substantial gains in potato productivity are achieved through the co-application of ZnO NPs and organic manures. This synergy represents a holistic approach that simultaneously optimizes the soil environment and the plant's internal physiology.

5.1. Biomass and Yield Components

The integration of organic composts, such as banana compost (BCo) or soybean compost (SCo), with micronutrients like zinc has been shown to markedly alleviate the biomass reduction caused by salinity (El-Ghamry et al., 2024). These composts enrich the soil with organic matter and increase the water-holding capacity, which complements the role of ZnO NPs in maintaining the plant's water status (Arora et al., 2024).

In field experiments, co-application strategies have led to significant increases in the number of tubers per plant, average tuber weight, and total tuber yield compared to stressed controls (Nazir et al., 2024). For example, the use of specialized composts with trace elements significantly improved the SPAD chlorophyll readings and the accumulation of Nitrogen (N), Phosphorus (P), and Potassium (K) in potato leaves, providing the necessary nutrients for robust tuber development (El-Ghamry et al., 2024).

Figure 2: Schematic Representation of ZnO Nanoparticle Foliar Application and Organic Manure Soil Amendments on Potato Growth Stages, Physiological Responses, and Tuber Productivity under Salinity Stress



5.2. Source-to-Sink Enhancement

A critical factor in potato yield is the efficient translocation of photo-assimilates from the leaves (source) to the tubers (sink). Salinity stress disrupts this process by reducing the photosynthetic rate and hindering the movement of sucrose (Shah et al., 2022).

ZnO NPs enhance this "sink strength" by maintaining the activity of enzymes involved in carbohydrate metabolism and promoting the synthesis of auxins that regulate tuber expansion (Alghamdi et al., 2022). When coupled with organic manure, which ensures a steady supply of moisture and nutrients, the plant can sustain higher rates of sucrose translocation even under saline conditions (Mahmoud et al., 2020). This combined treatment has been shown to stabilize the expression of sucrose transporter genes, ensuring that energy is effectively channeled into tuber bulking rather than just survival mechanisms (Hassan et al., 2024).

6. Impact on Tuber Quality and Nutritional Biofortification

The quality of the potato tuber is determined by its chemical composition, which includes starch content, protein levels, and the presence of health-promoting antioxidants. The application of ZnO NPs and organic manures has a profound impact on these qualitative traits.

6.1. Starch Synthesis and Dry Matter Content

Starch is the primary storage carbohydrate in potato tubers and a key indicator of quality for the processing industry. ZnO NPs play a vital role in starch metabolism by acting as a cofactor for enzymes like starch synthase, which is involved in the conversion of soluble sugars into starch (Mahmoud et al., 2020).

Research has shown that foliar application of ZnO NPs at the tuber initiation stage can increase the starch fraction in tubers significantly. Specifically, a 25 mg/L dose of ZnO NPs has been reported to increase starch content by over 50%, while higher doses up to 250 mg/L increased it by approximately 34% (Nazir et al., 2024). This enhancement in starch synthesis is often accompanied by an increase in tuber dry weight and specific gravity, making the crop more valuable for industrial processing (Soliman et al., 2025).

6.2. Antioxidant and Phenolic Profile

Under saline conditions, the accumulation of secondary metabolites such as phenolics and flavonoids serves as an internal defense mechanism for the plant. The exogenous application of ZnO NPs further enhances the concentration of these total phenolics and flavonoids in the tubers (Seleiman, Al-Selwey, et al., 2023).

These compounds not only provide resistance to oxidative stress within the plant but also improve the nutritional value of the potato for human consumption by providing natural antioxidant properties (Seleiman, Ahmad, et al., 2023). This bio-stimulatory effect of nanoparticles ensures that the tubers harvested from saline soils are not only viable but possess superior health-promoting characteristics compared to those grown under conventional mineral fertilization (Nazir et al., 2024).

6.3. Agronomic Biofortification with Zinc

Zinc deficiency is a major global health concern, and the biofortification of staple crops is a sustainable strategy to address this "hidden hunger" (Arora et al., 2024). Potato tubers naturally contain low levels of zinc, but foliar application of ZnO NPs can significantly increase Zn accumulation in the edible parts (Du et al., 2024).

Studies have demonstrated that ZnO NP application can raise Zn concentrations in various potato tissues, with tuber Zn levels reaching up to 65.5 ug/g dry weight (Nazir et al., 2024). Importantly, at appropriate dosages, these nanoparticles are processed by the plant into biologically available forms, ensuring that the tubers are safe for consumption while being nutritionally enriched to meet human dietary requirements (Du et al., 2024).

Table 3: Qualitative and Nutritional Improvements in Potato Tubers through Integrated ZnO NP and Organic Manure Application

Tuber Quality Parameter	**Impact of Salinity**	**Impact of ZnO NPs + Organic Manure**	**Functional Outcome**
Starch Content	Decreased	Increased by 30–50%	Improved Texture (Nazir et al., 2024)
Protein Content	Reduced	Enhanced	Higher Nutritional Value (Nazir et al., 2024)
Total Phenolics	Variable (Stress Response)	Significantly Increased	Higher Antioxidant Capacity (Nazir et al., 2024)
Zinc Concentration	Low	Increased (Biofortification)	Reduced Malnutrition (Du et al., 2024; Nazir et al., 2024)

7. Environmental Safety and Risk Assessment

While the benefits of ZnO NPs and organic manures are evident, the agricultural application of nanomaterials requires careful consideration of their environmental fate and potential toxicity (Du et al., 2024).

7.1. Ecotoxicological Thresholds

The efficacy of ZnO NPs is highly dose-dependent. While low concentrations (25–100 mg/L) stimulate growth and mitigate stress, excessive dosages can lead to phytotoxicity (Mahmoud et al., 2020). High doses of ZnO NPs have been observed to cause cellular abnormalities, such as vacuolation of root cells and a reduction in root biomass, likely due to the over-accumulation of Zinc ions (Seleiman, Ahmad, et al., 2023).

Therefore, determining the optimal concentration for different soil types and potato cultivars is essential for safe application to avoid disrupting the plant's metabolic equilibrium (Soliman et al., 2025).

7.2. Soil Microbial Integrity

Long-term exposure to metal oxide nanoparticles can potentially alter soil microbial community structures. Some studies have noted a reduction in microbial colony-forming units (CFUs) and CO_2 emissions following the addition of ZnO NPs, particularly in sandy loam soils (Du et al., 2024).

However, the inclusion of organic manure provides a significant protective effect for the soil microbiome. Organic matter provides a carbon source that stimulates microbial activity and serves as a buffer, reducing the direct exposure of sensitive microorganisms to the nanoparticles (Arora et al., 2024). This synergistic application ensures that soil health is maintained while providing the benefits of nano-fertilization (Ahmad et al., 2025).

7.3. Translocation and Food Safety

A critical concern for consumers is the potential for nanoparticle accumulation in the edible portions of the plant. Current research using X-ray diffraction and in-situ analysis indicates that when ZnO NPs are applied at moderate rates (e.g., 50 mg/kg), they do not necessarily penetrate the plant tissues in their nano-form (Du et al., 2024). Instead, they are likely dissolved into Zn^{2+} ions that are then incorporated into the plant's metabolic pathways. This suggests that the risk of direct nanoparticle ingestion from biofortified potatoes is minimal, provided that application protocols are strictly followed (Zaman et al., 2024).

8. Synthesis of Findings and Future Outlook

The integration of ZnO NPs and organic manures provides a comprehensive solution to the problem of potato cultivation in saline environments. This dual approach addresses both the root cause (soil salinity) and the symptoms (physiological and biochemical stress) of the problem. Organic manures remediate the soil structure, enhance the CEC, and revitalize the microbiome, while ZnO NPs fortify the plant's antioxidant defense, sustain photosynthesis, and enhance the synthesis of starch and other quality attributes (El-Ghamry et al., 2024).

The future of this technology lies in the development of "nanobiofertilizers," which combine the efficacy of nanomaterials with the biological benefits of organic amendments and beneficial microorganisms in a single formulation (Arora et al., 2024). Such products would allow for the controlled and targeted delivery of nutrients, minimizing waste and environmental impact while maximizing the productivity of salt-affected lands (Nazir et al., 2024).

Additionally, more research is needed to understand the long-term impacts of repeated nanoparticle applications on soil health and to optimize application timings such as nano-priming versus foliar sprays at specific growth stages to maximize the economic returns for farmers (Mahmoud et al., 2020). In conclusion, the synergistic use of ZnO nanoparticles and organic manures represents a sustainable, high-efficiency strategy that can help secure the future of potato production in the face of increasing global salinity (Seleiman, Ahmad, et al., 2023).

Conclusion

Salinity stress poses a serious threat to sustainable potato production by disrupting soil properties, impairing plant physiological processes, and reducing tuber yield and quality. The findings synthesized in this study demonstrate that an integrated application of zinc oxide nanoparticles (ZnO NPs) and organic manures offers an effective and environmentally sustainable strategy to mitigate the adverse effects of saline conditions on potato cultivation. Organic manures play a pivotal role in improving soil structure, enhancing cation exchange capacity, reducing sodium toxicity, and revitalizing beneficial soil microbial communities, thereby creating a more favorable rhizosphere environment. Concurrently, ZnO nanoparticles strengthen plant physiological resilience by maintaining photosynthetic activity, enhancing antioxidant defense systems, regulating hormonal balance, and improving nutrient uptake and translocation. The synergistic interaction between ZnO nanoparticles and organic amendments results in substantial improvements in plant growth, tuber yield, starch accumulation, antioxidant composition, and zinc biofortification, even under elevated salinity levels. Importantly, when applied at optimized doses, ZnO nanoparticles do not pose significant environmental or food safety risks, particularly when combined with organic manures that buffer potential nano-toxicity and support soil biological integrity.

Overall, the transition from conventional fertilizer-based practices toward an integrated nano-organic management approach represents a promising pathway for enhancing potato productivity, nutritional quality, and soil health in salt-affected agroecosystems. Future research should focus on long-term field evaluations, cultivar-specific responses, and the development of standardized nano-biofertilizer formulations to ensure economic feasibility and large-scale adoption. This integrated strategy has strong potential to contribute to climate-resilient agriculture and global food security in salinity-prone regions.

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