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NANO-ZINC FOR NUTRIENT MANAGEMENT: AN EMERGING NANOTECHNOLOGY APPROACH FOR ENHANCING CROP NUTRITION, GROWTH AND AGRICULTURAL PRODUCTIVITY

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ABSTRACT

Zinc (Zn) is an essential micronutrient required for normal plant growth, development, enzyme activation, protein synthesis, chlorophyll formation and several physiological and metabolic processes. However, zinc deficiency is a widespread nutritional constraint in agricultural soils, particularly in intensively cultivated areas, resulting in reduced crop productivity, poor grain quality and nutritional imbalance. Conventional zinc fertilizers, although widely used, often exhibit low nutrient-use efficiency due to fixation, precipitation, leaching and limited availability in soil. In this context, zinc nanoparticles (ZnNPs) have emerged as a promising nanotechnology-based approach for improving nutrient management and enhancing micronutrient-use efficiency in crop production. Owing to their small particle size, high surface-area-to-volume ratio and unique physicochemical properties, nano-zinc formulations may improve nutrient availability, absorption, translocation and utilization within plants. They can influence seed germination, root development, photosynthetic activity, antioxidant defence and reproductive growth when applied at appropriate concentrations. Furthermore, nano-zinc fertilizers offer opportunities for targeted nutrient delivery, reduced fertilizer losses and improved crop nutritional quality. However, their effectiveness depends on particle characteristics, application methods, crop species, soil properties and environmental conditions. This article discusses the importance of zinc in plant nutrition, the role of nano-zinc in nutrient management, its application strategies, potential benefits and associated challenges. The integration of nano-zinc technology with precision nutrient management may contribute to sustainable agriculture, improved fertilizer-use efficiency and biofortification of food crops.

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1. INTRODUCTION

Micronutrient management is an essential component of modern agricultural production, as the availability of essential nutrients directly influences plant growth, physiological development, crop productivity and nutritional quality. Among the essential micronutrients, zinc (Zn) plays a vital role in enzyme activation, protein synthesis, carbohydrate metabolism, photosynthesis, auxin production and maintenance of cellular membrane integrity. It also contributes to reproductive development, pollen viability and grain formation. However, zinc deficiency is a widespread nutritional constraint in agricultural soils, particularly in intensively cultivated regions. Factors such as alkaline soil reaction, high phosphorus availability, low organic matter content, calcareous soil conditions and continuous cropping reduce zinc availability and uptake by plants, resulting in chlorosis, stunted growth, shortened internodes, poor root development and reduced crop yield. Although conventional zinc fertilizers, particularly zinc sulphate, are widely used to correct this deficiency, their effectiveness is often limited by adsorption, precipitation, leaching and fixation processes in soil, which reduce nutrient availability and fertilizer-use efficiency. Consequently, the development of innovative nutrient delivery systems has become increasingly important for sustainable agriculture. In this context, nanotechnology has emerged as a promising approach for improving micronutrient management through the development of nanofertilizers that offer opportunities for enhanced nutrient availability, targeted delivery and improved nutrient-use efficiency. Nano-zinc, particularly zinc oxide nanoparticles (ZnO NPs), has attracted considerable attention as an emerging micronutrient formulation because of its small particle dimensions, high surface-area-to-volume ratio and distinctive physicochemical properties. These characteristics may influence nutrient dissolution, release of bioavailable zinc ions and interactions with soil and plant tissues, thereby supporting zinc uptake, translocation and utilization. Appropriate nano-zinc application has shown potential for improving seed germination, root and shoot development, chlorophyll content, photosynthetic activity, antioxidant defence mechanisms and biomass accumulation. Its application through seed priming, soil incorporation and foliar spraying provides different opportunities for improving crop nutrition, particularly under conditions of restricted soil zinc availability. Furthermore, nano-zinc has considerable potential in agronomic biofortification by enhancing zinc accumulation in edible plant parts and improving the nutritional quality of food crops. Its integration with conventional fertilizers, organic manures, biofertilizers and precision nutrient management practices may further contribute to balanced plant nutrition and sustainable crop production. Nevertheless, the effectiveness of nano-zinc depends on nanoparticle size, concentration, surface characteristics, formulation stability, crop species, soil properties and environmental conditions. Excessive application may cause phytotoxicity, oxidative stress and undesirable effects on beneficial soil microorganisms. Therefore, investigations into its long-term environmental behaviour, food safety, economic feasibility and crop-specific application requirements are essential. In this regard, the present article highlights the significance of nano-zinc in plant nutrition, its mechanisms of nutrient delivery, application strategies, potential benefits in crop production, role in nutritional biofortification and future prospects for sustainable nutrient management.

2. IMPORTANCE OF ZINC IN PLANT NUTRITION

Zinc is an essential micronutrient involved in numerous physiological and biochemical activities in plants. It plays a significant role in the activation of enzymes such as carbonic anhydrase, alcohol dehydrogenase and superoxide dismutase. It is also associated with auxin metabolism, particularly the synthesis and regulation of indole-3-acetic acid (IAA), which influences root development, cell elongation and plant growth. Zinc contributes to chlorophyll formation, photosynthetic activity, carbohydrate metabolism, protein synthesis and membrane stability. Zinc deficiency commonly occurs in calcareous, alkaline and phosphorus-rich soils, where its availability to plants is restricted. Deficiency symptoms include interveinal chlorosis, reduced leaf size, shortened internodes, stunted

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growth, delayed maturity and poor reproductive development. In cereals, zinc deficiency can reduce grain yield and nutritional quality. Therefore, maintaining adequate zinc availability through balanced nutrient management is essential for improving crop productivity and food nutritional security (Sturikova et al., 2018).

3. NANO-ZINC: CONCEPT AND CHARACTERISTICS

Nano-zinc generally refers to zinc-containing nanomaterials used for agricultural applications, particularly zinc oxide nanoparticles (ZnO NPs), elemental zinc nanoparticles and nano-formulated zinc fertilizers. These materials possess nanoscale dimensions, generally within the range of 1–100 nm, although agricultural formulations may contain larger aggregates. The distinctive properties of nano-zinc include a high surface-area-to-volume ratio, surface reactivity and the potential for controlled dissolution and nutrient release. These characteristics may improve zinc delivery to plant tissues compared with certain conventional formulations. Nano-zinc can release bioavailable Zn^{2+} ions through dissolution, which are subsequently involved in various metabolic processes. The behaviour of these nanoparticles depends on their size, shape, surface coating, concentration and synthesis method. Green synthesis using plant extracts, bacteria, fungi and other biological materials has gained attention as an alternative to conventional chemical synthesis. Such approaches may reduce the use of hazardous chemicals during nanoparticle production and offer opportunities for developing environmentally conscious agricultural inputs (Ravishankar et al., 2025).

4. MECHANISMS OF NANO-ZINC IN NUTRIENT MANAGEMENT

Nano-zinc contributes to plant nutrition through several interconnected mechanisms. Following soil or foliar application, zinc-containing nanoparticles may dissolve, release zinc ions and undergo transformations within the soil–plant environment. The released zinc becomes available for uptake and utilization in different physiological processes. At the cellular level, zinc participates in enzyme activation, protein synthesis, carbohydrate metabolism and antioxidant defence. It also supports the functioning of zinc-dependent transcription factors and other regulatory proteins. Appropriate zinc availability can improve photosynthetic efficiency, maintain membrane integrity and support the development of roots and shoots. Another important mechanism involves the interaction of nanoparticles with the rhizosphere. Soil pH, organic matter, microbial activity and mineral composition influence the dissolution, aggregation, mobility and bioavailability of nano-zinc. Certain formulations may improve nutrient availability and modify soil–microbe interactions, although these responses are dependent on application rate and environmental conditions (Lv et al., 2022).

5. APPLICATION OF NANO-ZINC IN CROP PRODUCTION

5.1 Seed Priming and Seed Treatment

Seed priming with nano-zinc is an emerging approach for improving seed germination, seedling establishment and early plant vigour. During seed treatment, seeds are exposed to an appropriately formulated nano-zinc suspension under controlled conditions. This may facilitate the initial availability of zinc during germination and support early metabolic activities. Nano-zinc seed treatment has been investigated for improving root and shoot development, seedling biomass and nutrient accumulation in different agricultural crops. Its effectiveness depends on seed characteristics, nanoparticle concentration, exposure duration and crop species. Excessive concentrations may inhibit germination or cause phytotoxic effects; therefore, optimization is essential.

5.2 Soil Application

Soil application of nano-zinc offers an opportunity to supplement zinc in deficient agricultural soils. Conventional zinc fertilizers, such as zinc sulphate, are frequently used to correct micronutrient deficiencies. However, zinc availability can decline through adsorption, precipitation and fixation, particularly under alkaline and calcareous soil conditions. Nano-zinc formulations are being investigated for their potential to improve zinc availability and provide a more targeted nutrient supply. Their performance depends on particle dissolution, soil characteristics, moisture

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conditions and interactions with organic and inorganic soil constituents. Combining nano-zinc with organic manures, compost and zinc-solubilizing microorganisms may offer additional opportunities for improving nutrient management. Nevertheless, the compatibility and effectiveness of such combinations require crop-specific field validation.

5.3 Foliar Application

Foliar application is one of the promising methods of delivering nano-zinc directly to plant leaves. It can be particularly useful when soil conditions restrict zinc availability or when rapid correction of micronutrient deficiency is required. Following foliar deposition, zinc-containing formulations may enter leaf tissues through cuticular and stomatal pathways, depending on particle properties and formulation characteristics. The absorbed zinc can subsequently participate in physiological and metabolic processes and may be transported to other plant organs. Recent research has examined the effectiveness of foliar-applied ZnO nanoparticles in improving crop zinc nutrition under rainfall conditions. Such studies highlight the importance of formulation stability, leaf retention, application timing and environmental conditions in determining nutrient absorption (Li et al., 2024).

5.4 Nano-Zinc in Crop Growth and Yield Improvement

Appropriate nano-zinc application may improve several growth and yield-related parameters, including plant height, leaf area, root biomass, chlorophyll content, flowering, grain formation and total biomass production. Zinc supports enzyme activities associated with photosynthesis, respiration and carbohydrate metabolism, thereby contributing to normal plant growth. Research has demonstrated promising responses to nano-zinc application in cereals, pulses, oilseeds and horticultural crops. In wheat, for example, zinc oxide nanoparticles have been investigated for improving plant zinc accumulation, chlorophyll content and grain nutritional quality. Similarly, studies in sorghum and other crops have reported improvements in growth parameters under suitable application conditions. However, the magnitude of these responses varies with crop genotype, soil fertility and nanoparticle concentration (Ravishankar et al., 2025).

6. NANO-ZINC FOR BIOFORTIFICATION AND NUTRITIONAL SECURITY

Zinc deficiency is not restricted to agricultural soils and plants; it also represents a significant nutritional challenge for human and animal populations. Consumption of zinc-deficient food crops can contribute to inadequate dietary zinc intake, particularly in populations dependent on cereal-based diets. Nano-zinc technology offers potential opportunities for agronomic biofortification by increasing zinc accumulation in edible plant parts. Foliar application and suitable soil-based formulations may improve zinc concentration in cereal grains, pulses, vegetables and fruits. Improving grain zinc concentration while maintaining desirable yield and quality characteristics could contribute to better nutritional outcomes. The integration of nano-zinc with conventional biofortification programmes, zinc-efficient cultivars and balanced fertilizer management may provide a comprehensive strategy for improving food nutritional quality. Nevertheless, the nutritional bioavailability of accumulated zinc should also be evaluated because total grain zinc concentration does not necessarily indicate the amount available for human absorption.

7. CHALLENGES AND ENVIRONMENTAL CONSIDERATIONS

Despite its promising applications, nano-zinc technology faces several scientific and practical challenges. The effectiveness of nanoparticles depends strongly on their size, concentration, shape, surface properties, formulation and environmental conditions. An appropriate concentration may stimulate plant growth, whereas excessive application can induce oxidative stress, damage cellular structures, inhibit root development and negatively affect plant metabolism. The behaviour of nano-zinc in soil also requires careful consideration. Its accumulation and transformation may influence beneficial soil microorganisms, microbial diversity, nutrient cycling and rhizosphere processes. Repeated application without proper monitoring may create unintended environmental consequences.

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Another major challenge is the lack of standardized recommendations for nano-zinc application across different crops and agroecological conditions. Long-term field experiments are required to establish suitable concentrations, application methods, residual behaviour and economic feasibility. Therefore, nano-zinc should be integrated into existing nutrient management programmes based on soil testing and crop requirements rather than considered a universal replacement for conventional fertilizers (Lv et al., 2022; Ravishankar et al., 2025).

8. FUTURE PROSPECTS

Future research on nano-zinc should focus on developing stable, cost-effective and environmentally compatible formulations with improved nutrient delivery characteristics. Green synthesis, nano-encapsulation, biodegradable coatings and controlled-release technologies may provide opportunities for enhancing the effectiveness of zinc-based nanofertilizers. The integration of nanotechnology with precision agriculture, remote sensing, soil nutrient mapping and artificial intelligence could support site-specific micronutrient management. Such approaches may help determine crop zinc requirements, identify deficiency symptoms and optimize fertilizer application according to field conditions. Furthermore, the combination of nano-zinc with zinc-solubilizing bacteria, biofertilizers and organic nutrient sources deserves greater scientific attention. Multilocation field trials, food safety assessments and long-term soil monitoring will be essential for establishing the practical suitability of these technologies. Responsible integration of nano-zinc with conventional nutrient management could contribute to improved nutrient-use efficiency, crop productivity and agricultural sustainability.

9. CONCLUSION

Nano-zinc represents an emerging nanotechnology-based approach for improving micronutrient management and addressing zinc deficiency in agricultural production systems. Its distinctive physicochemical properties offer opportunities for improving zinc delivery, nutrient absorption and utilization in plants. Applications through seed treatment, soil incorporation and foliar spraying have demonstrated promising potential for enhancing seedling vigour, root development, photosynthetic activity, crop growth and grain nutritional quality. Furthermore, nano-zinc may contribute to agronomic biofortification and improved nutritional security by increasing zinc accumulation in edible plant parts. However, its successful agricultural application requires a comprehensive understanding of nanoparticle behaviour, crop-specific responses, optimal concentrations and environmental interactions. Excessive or unregulated application may adversely affect plant growth and soil microbial communities. Therefore, future research should emphasize standardized formulations, dose optimization, long-term field validation and environmental safety assessment. Integrating nano-zinc with soil-test-based fertilizer recommendations, organic nutrient sources and precision agriculture technologies could establish a more efficient and sustainable approach to micronutrient management in modern crop production.

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