Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 06, Issue: 01 (JAN-FEB, 2026)
Available online at http://www.agriarticles.com
©Agri Articles, ISSN: 2582-9882

Micronutrient Nano-Priming with Iron and Zinc in Plants

*Saujanya Roy
M.Sc. (Ag) Scholar, Dept. of Seed Science and Technology, Odisha University of Agriculture & Technology, Bhubaneswar, Odisha-751003, India
*Corresponding Author's email: kirtidananadamani@gmail.com

Micronutrient seed priming is a cost-effective and efficient technique to enhance crop growth, yield, and stress tolerance by improving the nutrient status of plants. Farooq et al. (2012a, b) highlighted that seed priming with micronutrients such as zinc (Zn), boron (B), iron (Fe), manganese (Mn), molybdenum (Mo), copper (Cu), and chlorine (Cl) can significantly improve germination, seedling growth, nutrient uptake, and grain yield under both normal and stress conditions. For instance, seed priming with $ZnSO_4$ has been shown to increase grain yield, protein content, and Zn accumulation in wheat grains (Seddigh et al., 2016). Similarly, boron seed priming enhances seed germination, seedling vigour, and yield attributes in crops like wheat and rice (Chakraborty and Bose, 2018; Farooq et al., 2011). Iron seed priming improves nutrient concentration, seedling growth, and yield in maize and wheat (Imran et al., 2013; Reis et al., 2018). Manganese seed priming enhances seedling development, nutrient translocation, and yield traits in crops such as wheat and carrot (Munawar et al., 2013; Sarakhsi and Behrouzyar, 2014). Molybdenum seed priming has been reported to improve nodulation, nitrogen fixation, and yield in legumes like chickpea and mung bean (Mohandas, 1985; Umair et al., 2011).

Nanopriming

Seed nano-priming is an innovative agricultural technique that utilizes nanomaterials, primarily nanoparticles, to enhance seed germination, plant growth, and stress resistance. Unlike conventional seed priming, which typically involves water or nutrient solutions, nano-priming employs nanoformulations where nanoparticles may be absorbed by seeds or retained as a coating. This process has shown promising results in improving seed metabolism, germination synchronization, and plant vigor, while reducing the need for pesticides and fertilizers (Mahakham et al., 2017; Acharya et al., 2020). For instance, Mahakham et al. (2017) demonstrated that silver nanoparticles synthesized using kaffir lime leaf extracts significantly improved rice seed germination, seedling vigor, and plant biomass. Similarly, Acharya et al. (2020) reported that watermelon seeds primed with biogenic silver nanoparticles exhibited enhanced germination, growth, yield, and quality across multiple locations.

Approach on Zinc oxide induced nano priming of seeds

The study conducted by Hassan and Sattar (2026) aimed to evaluate the impact of zinc oxide nanoparticles (ZnO-NPs) on the functional, structural, and hydration properties of germinated cowpea beans (Vigna unguiculata L. Walp). Cowpea is a leguminous plant rich in macronutrients, essential amino acids, and bioactive compounds, making it a valuable source of nutrition. However, the presence of antinutritional factors such as phytates and oxalates can hinder nutrient absorption. Germination has been shown to improve the functional properties of legumes by enhancing enzymatic activity and reducing antinutritional factors

(Sattar et al., 2021). This study explored the potential of ZnO-NPs as seed primers to further enhance the properties of germinated cowpea beans for food industry applications.

Mechanism

Zinc oxide nanoparticles (ZnO-NPs) are known for their antimicrobial, antiviral, and growth-promoting properties (Sharmin et al., 2021; Abou El-Nasr et al., 2025). In this study, ZnO-NPs were hypothesized to interact with proteins, polysaccharides, and lipids in cowpea beans, leading to structural and functional modifications. These interactions were expected to enhance hydration, emulsifying, foaming, and color properties, making the germinated cowpea flour suitable for use in nutraceuticals and functional food formulations.

Methods

1. **Preparation of ZnO-NP Suspension** Zinc oxide nanoparticle powder (0.25 g) was dissolved in 500 mL of distilled water, shielded from light and heat using aluminium foil, and sonicated for 30 minutes at 35°C to prevent aggregation. ZnO-NP concentrations of 0, 20, 40, 60, 80, and 100 ppm were prepared for seed treatment (Islam et al., 2023).
2. **Germination Process** Cowpea beans were rinsed, treated with 4% sodium hypochlorite solution to remove fungal contaminants, and soaked in ZnO-NP solutions for 2 hours. After a 10-hour hydration period, seeds were incubated on moistened jute fabric at 25 ± 2°C for two days. Sprouting was assessed by measuring root length and sprouting percentage. The sprouted seeds were ground into fine powder and stored at 4°C for further analysis (Islam et al., 2023).
3. **Functional Property Analysis**

- **Emulsion Activity (EA) and Stability (ES):** Emulsion activity and stability were measured using oil-water mixtures and centrifugation (Sattar et al., 2017).
- **Foaming Capacity (FC) and Stability (FS):** Foam properties were evaluated by whipping flour-water mixtures and measuring foam volume and stability over time (Sattar et al., 2017).

4. **Hydration and Fat Absorption Properties**

- **Water Absorption Capacity (WAC) and Water Holding Capacity (WHC):** Flour samples were mixed with water, incubated, and centrifuged to measure hydration properties (Marium & Iqbal, 2024).
- **Swelling Capacity (SC) and Swelling Index (SI):** Flour samples were soaked in water, and changes in volume and weight were recorded (Liu et al., 2025).
- **Fat Absorption Capacity (FAC):** Flour samples were mixed with oil, centrifuged, and weighed to determine lipid absorption (Marium & Iqbal, 2024).

5. **Flow Properties** Bulk density (BD), tapped density, Hausner ratio (HR), and Carr's index (CI) were measured to assess the flowability of the flour (Hao, 2015).
6. **Colour Profile** A Hunter Lab colorimeter was used to measure lightness (L*), redness (a*), and yellowness (b*) of the flour (Yi et al., 2017).
7. **Structural Analysis**

- **FTIR Spectroscopy:** FTIR was used to identify molecular interactions and functional group changes in the flour (Kaur & Gill, 2021).
- **SEM Imaging:** Scanning electron microscopy (SEM) was employed to observe microstructural changes in the flour (Geremew et al., 2025).

Observations

1. **Functional Properties**

- **Emulsion Activity (EA):** ZnO-NPs improved EA at moderate concentrations (20–40 ppm), with the highest EA observed at 40 ppm (38.61 ml/100 ml). Excessive concentrations (80 ppm) reduced EA due to protein aggregation (Yang et al., 2025).
- **Emulsion Stability (ES):** ES was highest at 80 ppm (38.41 ml/100 ml), indicating that higher ZnO-NP concentrations enhance protein-nanoparticle networks (Fan et al., 2025).

- **Foaming Properties:** Germination improved FC and FS, while ZnO-NPs showed a dose-dependent effect. High concentrations (100 ppm) increased FS (119 ml/100 ml) but reduced FC (11 ml/100 ml) due to protein rigidity (Han et al., 2024).

2. **Hydration and Fat Absorption Properties**

- Germination increased WAC, WHC, SC, SI, and FAC due to enzymatic hydrolysis and exposure of hydrophilic and hydrophobic sites (Zhao et al., 2024).
- ZnO-NPs further enhanced hydration and fat absorption properties at moderate concentrations (20–40 ppm), but excessive concentrations led to reduced swelling behaviour due to particle aggregation (Liu et al., 2025).

3. **Flow Properties**

- Germination improved flowability by reducing particle cohesiveness (Hao, 2015).
- ZnO-NPs at 20–40 ppm further enhanced flow properties, while higher concentrations (80–100 ppm) caused particle aggregation, reducing flowability (Garcia Tobar et al., 2024).

4. **Color Profile**

- Germination darkened the flour due to enzymatic browning (Cakir et al., 2025).
- ZnO-NPs at 40–60 ppm stabilized the colour, reducing browning and improving lightness (Roobab & Maqsood, 2024).

5. **Structural Analysis**

- **FTIR:** ZnO-NPs induced structural changes in proteins and polysaccharides, with the strongest interactions observed at 60 ppm (Kaur & Gill, 2021).
- **SEM:** ZnO-NPs caused progressive structural breakdown, increasing porosity and fragmentation, with the most significant changes at 100 ppm (Geremew et al., 2025).

Chitosan Stabilised Iron Oxide Nano priming

The study conducted by Nurfarwizah Adzuan Hafiz et al. (2025) addresses the challenges posed by climate change and nutrient limitations on seed germination and early seedling establishment. It explores a sustainable nano priming approach using chitosan-stabilized iron oxide nanoparticles (CS-FeNPs) to enhance lettuce (Lactuca sativa) seedling performance and economic feasibility. The research aims to optimize the priming duration for lettuce seeds, improve nanoparticle stability, and assess the scalability of the process for agricultural applications.

Mechanism of Action

The enhanced germination and seedling vigour observed in the study are attributed to a sequence of physicochemical and biological processes:

1. **Electro steric Stabilization**:

- Chitosan forms a conformal shell around FeNPs, imparting steric and electrostatic stabilization. This prevents aggregation and ensures uniform dispersion in aqueous solutions (Hafiz et al., 2025).
- The chitosan coating creates a positive surface charge (+35.5 mV) and reduces the hydrodynamic size of the nanoparticles to ∼112.7 nm, enhancing their colloidal stability and bioavailability.

2. **Seed-NP Interaction**:

- Chitosan's protonated $-NH_3^+$ groups interact with anionic components of the seed coat, anchoring the nanoparticles to the seed surface and facilitating penetration through microscopic apertures (Hafiz et al., 2025).

3. **Controlled Iron Release**:

- The chitosan shell acts as a controlled-release matrix, gradually liberating Fe^{2+}/Fe^{3+} ions that are absorbed by the seed. These ions serve as cofactors for germination-related enzymes, such as catalase and peroxidase, which enhance metabolic activation and reserve mobilization (Hafiz et al., 2025).

4. **Reactive Oxygen Species (ROS) Signalling**:

- Trace amounts of ROS generated via Fenton reactions act as signalling molecules, triggering aquaporin gene expression and expansion protein production. This enhances water permeability and cell wall loosening, promoting rapid cell elongation and seedling growth (Hafiz et al., 2025).

5. **Chitosan Bioactivity**:

- Chitosan fragments bind to pattern recognition receptors in seed tissues, inducing defence-like responses that upregulate antioxidant systems and modulate phytohormone balances, favouring germination over dormancy (Hafiz et al., 2025).

Methods

1. **Synthesis of CS-FeNPs**:

- CS-FeNPs were synthesized using a low-energy co-precipitation method. Chitosan was dissolved in acetic acid, and iron salts ($FeCl3·6H2O$ and $FeCl2·4H2O$) were dissolved in deionized water. The iron solution was purged with nitrogen gas to minimize oxidation, mixed with the chitosan solution, and precipitated using ammonia at pH ~11. The nanoparticles were washed, centrifuged, dried, and stored (Hafiz et al., 2025).

2. **Characterization**:

- Transmission Electron Microscopy (TEM) and Dynamic Light Scattering (DLS) were used to analyse particle morphology, size, and zeta potential. Chitosan-coated FeNPs exhibited improved dispersion and colloidal stability compared to uncoated FeNPs (Hafiz et al., 2025).

3. **Seed Priming Procedure**:

- Lettuce seeds were sterilized and primed in a 1 ppm CS-FeNP suspension for varying durations (2, 6, 8, 16, and 24 hours). After priming, seeds were air-dried and sown in controlled conditions. Germination percentage, root length, shoot length, and fresh weight were measured (Hafiz et al., 2025).

4. **Statistical Analysis**:

- Data were analysed using one-way ANOVA and Fisher's LSD post hoc test, with significance set at $p < 0.05$ (Hafiz et al., 2025).

Observations

1. **Physicochemical Properties**:

- CS-FeNPs exhibited a uniform core size of ~102.8 nm, reduced hydrodynamic size (112.7 nm), and high zeta potential (+35.5 mV), indicating enhanced colloidal stability and reduced aggregation compared to uncoated FeNPs (Hafiz et al., 2025).

2. **Optimal Priming Duration**:

- The 8-hour priming duration yielded the highest germination rate (96.67%) and significantly improved root length (3.02 cm), shoot length (5.18 cm), and fresh biomass accumulation. Longer durations (16 and 24 hours) reduced performance, likely due to overstimulation or metabolic imbalance (Hafiz et al., 2025).

3. **Economic Feasibility**:

- The pilot-scale process for CS-FeNP synthesis and seed priming was estimated to cost $4.40 per 10-L batch, making it significantly more cost-effective than conventional methods such as hydropriming or hormonal priming (Hafiz et al., 2025).
- The study by Hafiz et al. (2025) demonstrates that CS-FeNP nano priming is a sustainable and economically viable strategy for enhancing seed germination and seedling vigour in lettuce. The optimized 8-hour priming duration ensures maximum benefits while avoiding overexposure-induced stress. The findings provide a foundation for further research into the biochemical mechanisms underlying the observed improvements and the scalability of this technology for real-world agricultural applications.

Future Prospects

- **Key role in climate-resilient agriculture**

With increasing climate variability, micronutrient priming is expected to become an important strategy for improving crop resilience against drought, salinity, and heat stress.

- **Integration with advanced priming technologies**

Combining micronutrient priming with nano-priming, magneto-priming, and bio-priming can enhance nutrient delivery efficiency and physiological responses, leading to next-generation seed enhancement technologies.

- **Advances in molecular and omics research**

Future studies using genomics, proteomics, and metabolomics will help clarify the molecular mechanisms behind micronutrient-induced stress tolerance and growth enhancement.

- **Support for sustainable and low-input farming**

Micronutrient priming aligns well with sustainable agriculture by reducing fertilizer use, minimizing nutrient losses, and lowering environmental pollution.

- **High adoption potential in developing regions**

Growing awareness, increasing seed priming markets, and suitability for smallholder farming systems indicate strong future adoption, particularly in Asia-Pacific and African countries.

Conclusion

Micronutrient seed priming emerges as an effective, economical, and environmentally sustainable approach for enhancing seed quality, crop establishment, and overall agricultural productivity. By supplying essential micronutrients at the earliest stages of plant growth, this technique improves germination, seedling vigor, nutrient uptake efficiency, and tolerance to abiotic stresses such as drought and salinity. The reviewed studies and experimental evidence demonstrate that micronutrient priming enhances key physiological and biochemical processes, including enzyme activation, antioxidant defense, and metabolic regulation, leading to improved yield and nutritional quality of crops. Compared to conventional fertilization practices, seed priming requires minimal input, reduces nutrient losses, and ensures uniform nutrient delivery, making it particularly suitable for resource-limited and stress-prone farming systems. Despite certain limitations related to dosage optimization, crop specificity, and technical precision, continued advancements in priming protocols and integration with modern technologies such as nano-priming and magneto-priming are addressing these challenges. With growing concerns over climate change, soil degradation, and food security, micronutrient seed priming holds significant promise as a climate-resilient and low-input agricultural strategy. Overall, micronutrient seed priming represents a practical and scientifically sound tool for sustainable seed enhancement and crop improvement, with strong potential for widespread adoption in future agricultural systems.

References

1. do Espirito Santo Pereira A, Caixeta Oliveira H, Fernandes Fraceto L and Santaella C. 2021. Nanotechnology potential in seed priming for sustainable agriculture, *Nanomaterials*, *11*(2), p.267.
2. Nile S H, Thiruvengadam M, Wang Y, Samynathan R, Shariati M A, Rebezov M, Nile A, Sun M, Venkidasamy B, Xiao J and Kai G. 2022. Nano-priming as emerging seed priming technology for sustainable agriculture—recent developments and future perspectives, *Journal of nanobiotechnology*, *20*(1), p.254.
3. Majda C, Khalid D, Aziz A, Rachid B, Badr A S, Lotfi A and Mohamed B. 2019. Nutri-priming as an efficient means to improve the agronomic performance of molybdenum in common bean (Phaseolus vulgaris L.), *Science of the Total Environment*, *661*, pp.654-663.
4. Amir M, Prasad D, Khan F A, Khan A and Ahmad B. 2024. Seed priming: An overview of techniques, mechanisms, and applications.

5. Devika O S, Singh S, Sarkar D, Barnwal P, Suman J and Rakshit A. 2021. Seed priming: a potential supplement in integrated resource management under fragile intensive ecosystems, *Frontiers in Sustainable Food Systems*, *5*, p.654001.
6. Adzuan Hafiz N, Sembada A A, Osman M S, Abu Bakar N F, So'aib M S and Lenggoro I W. 2026. Optimizing Nanopriming Duration: Chitosan-Stabilized Iron Oxide Enhances Lettuce Seedling Performance and Cost-Effectiveness, *Chemistry & Biodiversity*, *23*(1), p.e02426.
7. Hassan Z and Sattar D E S. 2026. Zinc Oxide Nanoparticle-Induced Modifications in the Functional and Structural Properties as a Seed Primers of Sprouted Cowpea Beans (Vigna unguiculata L. Walp), *BioNanoScience*, *16*(2), p.143.