*International Journal of Plant & Soil Science*

***Volume 38, Issue 5, Page 72-92, 2026; Article no.IJPSS.157486***
***ISSN: 2320-7035***

# Zinc Nutrition as a Driver of Growth, Productivity, and Nutritional Quality in Vegetable Crops

**Surender Kumar [a], Burada Raja [b], Mohit Kashyap [c++*], Satish Chandra Narayan [d#], Rahul Prajapati [e†], Krupali Jagadala [f#], Abhishek Tiwari [g#] and Ashutosh Kumar [h‡]**

[a] *Department of Botany, Pt. N.R.S. Govt. College, Rohtak, Haryana, -124001, India.*
[b] *Vegetable Science, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir (SKUAST-K), India.*
[c] *Department of Soil Science, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya Palampur, 176062, India.*
[d] *Regional Research Station, Madhopur (RPCAU, Pusa)-845454, India.*
[e] *School of life Sciences and Biotechnology, Chhatrapati Shahuji Maharaj University, Kanpur, India.*
[f] *Department of Plant Physiology, College of Agriculture, OUAT Chiplima, Odisha University of Agriculture and Technology (OUAT Chiplima)-768026, India.*
[g] *Department of Agricultural Sciences, School of Agricultural Sciences and Engineering, IFTM University, Moradabad, Uttar Pradesh, India.*
[h] *KVK Narkatiyaganj, RPCAU Pusa, India.*

***Authors' contributions***

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

***Article Information***

DOI: https://doi.org/10.9734/ijpss/2026/v38i56065

**Open Peer Review History:**
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/157486

***Review Article***

***Received: 07/03/2026***
***Accepted: 29/04/2026***
***Published: 30/04/2026***

---

*[++] Ph.D. Research Scholar; [#] Assistant Professor; [†] Research Scholar; [‡] SMS, Horticulture Vegetables;*
**Corresponding author: E-mail: mmkashyap222@gmail.com;*

***Cite as:*** *Kumar, S., Raja, B., Kashyap, M., Narayan, S. C., Prajapati, R., Jagadala, K., … Kumar, A. (2026). Zinc Nutrition as a Driver of Growth, Productivity, and Nutritional Quality in Vegetable Crops. International Journal of Plant & Soil Science, 38(5), 72–92. https://doi.org/10.9734/ijpss/2026/v38i56065*

## Abstract

Zinc is a vital micronutrient for vegetable crops, playing a crucial role in enhancing growth, productivity, and nutritional quality. This review explores the significance of zinc in vegetable crop cultivation, emphasizing its biochemical functions, including enzyme activation, protein synthesis, and stress tolerance. Zinc contributes to key plant metabolic processes, improving overall plant vigor, root development, and fruit production. However, zinc deficiency, widespread in many agricultural soils, leads to stunted growth, poor yield, and reduced crop quality, directly impacting food security and human nutrition. The review examines various zinc supplementation strategies, including soil application, foliar spraying, and biofortification techniques, with an emphasis on optimizing zinc levels for different vegetable crops. Zinc biofortification offers a promising approach to improving the nutritional content of vegetables, addressing the worldwide issue of micronutrient malnutrition. Furthermore, the paper highlights zinc interactions with other nutrients and discusses sustainable practices for efficient zinc management, such as integrated nutrient management (INM) and exactitude agriculture. Future research directions include advancements in zinc-efficient crop breeding, nano-zinc fertilizers, and technologies for better monitoring and management. This review provides comprehensive insights into the role of zinc in vegetable crops, offering valuable recommendations for enhancing productivity, quality, and nutritional value for global agricultural sustainability and human health.

*Keywords: Zinc; nutritional quality; vegetable crops; biofortification; growth; productivity.*

## 1. Introduction

Micronutrients are required by plants in trace amounts but are indispensable for sustaining growth, yield, and quality. Elements such as zinc (Zn), iron, boron, copper, manganese, and molybdenum regulate key physiological and metabolic processes, including chlorophyll synthesis, photosynthesis, reproductive development, and enzyme activation, thereby supporting both vegetative growth and successful seed and fruit production (Zewide & Sherefu, 2021; Monib et al., 2023; Panchal & Maitreya, 2023). Adequate and balanced micronutrient supply, alongside macronutrients, is therefore fundamental to modern agriculture and high quality vegetable production (Zewide & Sherefu, 2021; Panchal & Maitreya, 2023; Abedi et al., 2022; Bhatt et al., 2020).

Among micronutrients, zinc occupies a particularly important place. Zn is a structural or regulatory component of many enzymes and proteins and is involved in carbohydrate and protein metabolism, auxin (growth hormone) synthesis, chlorophyll biosynthesis, pollen formation, membrane integrity, and resistance to biotic and abiotic stresses (Hacisalihoglu, 2020; Saleem et al., 2022; Hosamani et al., 2020; Tayyiba et al., 2021). Even though it is needed in small quantities, Zn strongly influences biomass production, yield, and product quality across diverse crops (Saleem et al., 2022; Hosamani et al., 2020; Tayyiba et al., 2021). In vegetable crops, zinc nutrition has been linked to improved seedling vigor, flowering, fruit set, yield, and shelf life, as well as better nutritional composition of edible parts (Pankaj & Nirala, 2024; Monib et al., 2023; Ravishankar et al., 2025).

Globally, micronutrient deficiencies in soils especially Zn have become widespread due to intensive cropping, reliance on high analysis NPK fertilizers, soil erosion, and depletion of native nutrient reserves (Rana et al., 2024; Panchal & Maitreya, 2023). It is estimated that roughly one third to one half of cultivated soils are Zn deficient, leading to reduced crop productivity and low Zn concentrations in edible tissues, with direct consequences for human nutrition and “hidden hunger” (Noulas et al., 2018; Rana et al., 2024; Khan et al., 2022; Younas et al., 2022). Approximately 17–20% of the world’s population is at risk of dietary Zn deficiency, contributing to impaired immune function, stunting, and increased morbidity, particularly in low income regions where plant foods are the main dietary component (Hacisalihoglu, 2020; Khan et al., 2022; Praharaj et al., 2021). Enhancing Zn nutrition of vegetable crops thus offers a dual benefit: higher yields and improved Zn density and overall nutritional value of vegetables for human diets (Noulas et al., 2018; Rana et al., 2024; Younas et al., 2022; Ahmed et al., 2024; Sangeetha et al., 2022).

The present review focuses on the role of zinc in growth, yield, and nutritional quality of vegetable crops, with the following objectives: (i) to summarize the physiological and biochemical functions of Zn relevant to vegetable species; (ii) to synthesize evidence on the effects of Zn supply on vegetative growth, reproductive development, and yield formation; (iii) to examine how Zn fertilization and biofortification strategies influence mineral composition and health related phytochemicals in vegetables; and (iv) to highlight agronomic and biofortification approaches that can improve Zn use efficiency and contribute to sustainable vegetable production and nutritional security (Saleem et al., 2022; Poudel et al., 2024; Pankaj & Nirala, 2024; Ahmed et al., 2024; Hassan et al., 2020).

## 2. Zinc: A Vital Micronutrient for Vegetable Crops

### 2.1 Biochemical Functions of Zinc in Plants

Zinc is a structural, catalytic and regulatory cofactor for hundreds of enzymes, the only element present in all six major enzyme classes (Saleem et al., 2022; Tayyiba et al., 2021; Natasha et al., 2022). It activates enzymes involved in protein synthesis, nucleic acid metabolism and gene regulation, stabilizes ribosomes, RNA and DNA, and maintains membrane integrity (Saleem et al., 2022; Tayyiba et al., 2021; Natasha et al., 2022). Zn-dependent enzymes and proteins participate in chlorophyll biosynthesis, pigment protection and carbonic anhydrase activity, which are essential for photosynthetic $CO_2$ fixation and chloroplast function (Hassan et al., 2020; Jamali & Zia-Ul-Hassan, 2025; Tayyiba et al., 2021; Smaoui et al., 2023).

Zinc plays key roles in photosynthesis and carbohydrate metabolism, including carbonic anhydrase, aldolase and dehydrogenases that drive carbon metabolism, sugar–starch interconversion, and energy production (Hassan et al., 2020; Tayyiba et al., 2021; Natasha et al., 2022; Gondal, 2021). Through these pathways Zn influences nitrogen metabolism, auxin synthesis, pollen formation and overall metabolic efficiency, all of which are critical for high-performing vegetable crops (Tayyiba et al., 2021; Jalal et al., 2024; Natasha et al., 2022; Mapodzeke et al., 2021).

### 2.2 Zinc Role in Enhancing Growth and Development

Adequate Zn improves root development and architecture, enhancing root length, biomass and branching, thereby supporting water and nutrient uptake (Jalal et al., 2024; Natasha et al., 2022; Mapodzeke et al., 2021). It increases leaf area, chlorophyll content and photosynthetic rate, which translate into greater vegetative vigor and biomass accumulation (Hassan et al., 2020; Smaoui et al., 2023; Jan et al., 2022; Pankaj & Nirala, 2024).

Zinc is also crucial for reproductive development: it supports pollen formation, pollen tube growth, flower initiation and fruit set, with deficiency often causing reduced flowering, poor fruit development and lower yields in crops including tomato, cucumber, okra and other vegetables (Tayyiba et al., 2021; Jalal et al., 2024; Pankaj & Nirala, 2024).

### 2.3 Stress Tolerance and Disease Resistance

Zinc markedly enhances tolerance to abiotic stresses such as drought, salinity, heat and heavy metals by improving cell membrane stability, stomatal regulation, water relations, osmotic adjustment, and boosting enzymatic and non-enzymatic antioxidant systems (Hassan et al., 2020; Jamali & Zia-Ul-Hassan, 2025; Jan et al., 2022; Hassan et al., 2022). Zn nutrition protects the photosynthetic apparatus under stress, maintains chlorophyll and carotenoids, and reduces oxidative damage (Hassan et al., 2020; Jamali & Zia-Ul-Hassan, 2025; Jan et al., 2022).

For biotic stresses, Zn contributes to plant defense by supporting Zn-requiring antioxidant enzymes (e.g., superoxide dismutases) and Zn-finger proteins involved in immune signaling and stress-responsive gene regulation, often reducing disease severity and pest damage (Han et al., 2021; Cabot et al., 2019; Pandya et al., 2023; Gondal, 2021).

## 3. Zinc Deficiency: Symptoms, Causes and Impact on Vegetable Crops

### 3.1 Visual and Physiological Symptoms of Zinc Deficiency

Zinc (Zn) deficiency in plants typically manifests first on younger leaves due to the limited mobility of Zn within plant tissues (Hafeez et al., 2013; Tayyiba et al., 2021; Nandal & Solanki, 2021). The most common visual symptoms include interveinal chlorosis, characterized by yellowing between leaf veins, along with mottling, bronzing, and bleaching of leaf tissues (Hafeez et al., 2013; Sharma et al., 2013; Tayyiba et al., 2021). As the deficiency progresses, plants often exhibit stunted growth, reduced internodal elongation, rosetting or “little leaf” symptoms, and a general reduction in leaf size (Hafeez et al., 2013; Sharma et al., 2013; Tayyiba et al., 2021; Nandal & Solanki, 2021). In severe cases, necrotic spots and leaf tip burn may develop, further impairing plant growth and productivity (Saleem et al., 2022; Hafeez et al., 2013).

From a physiological perspective, Zn deficiency adversely affects key metabolic and biochemical processes, including photosynthesis, enzyme activation, and auxin synthesis, ultimately leading to poor root development, delayed maturity, and overall plant weakness (A. et al., 2020; Saleem et al., 2022; Tayyiba et al., 2021; Mattiello et al., 2015). In vegetable crops, these physiological disruptions are reflected in reduced vegetative vigor, impaired flowering, smaller fruit size, and significant yield losses (Tayyiba et al., 2021; Pankaj & Nirala, 2024).

### 3.2 Consequences for Vegetable Productivity and Quality

Zinc deficiency reduces biomass production and can depress crop yield by 25–35% in sensitive crops under deficient soils (A. et al., 2020; Sharma et al., 2013). In vegetable crops, Zn deficiency decreases number and size of fruits or heads, lowers marketable yield, and results in small, misshapen produce with poor texture and shelf life (Saleem et al., 2022; Tayyiba et al., 2021; Pankaj & Nirala, 2024). Product quality is further reduced by lower concentrations of Zn and other nutrients in edible parts, contributing to inferior nutritional value (Saleem et al., 2022; Younas et al., 2022; Pankaj & Nirala, 2024). Even “hidden” or marginal deficiencies without clear visual symptoms can significantly reduce yield and quality (Sharma et al., 2013).

### 3.3 Geographical Prevalence and Global Food Security

Zinc deficiency is one of the most widespread micronutrient disorders in soils worldwide, affecting roughly 30–50% of agricultural lands, particularly in calcareous, high-pH, sandy, intensively cropped and rice-based soils (A. et al., 2020; Saleem et al., 2022; Nandal & Solanki, 2021; Muhammad et al., 2022). In India, large soil surveys indicate about 38–50% of soils are Zn-deficient, with strong spatial variation across states (A. et al., 2020; N et al., 2019; Khokhar et al., 2024).

These Zn-deficient soils produce vegetables and other foods with low Zn content, closely mirroring high rates of human Zn deficiency; an estimated 17–25% of the global population is at risk, especially in cereal- and vegetable-based diets of low-income regions (Khan et al., 2022; Younas et al., 2022; N et al., 2019; Ishfaq et al., 2021). This “hidden hunger” contributes to stunting, impaired immunity and increased morbidity, intensifying global food insecurity and malnutrition despite adequate calorie supply (Khan et al., 2022; Younas et al., 2022; Hacisalihoglu, 2020; Ishfaq et al., 2021).

**Table 1. Functional roles of zinc in vegetable crops**

| Functional area | Main Zn-related roles in plants | Citations |
|---|---|---|
| Biochemical functions | Enzyme activation, protein & nucleic acid synthesis, chlorophyll and pigment formation | (Saleem et al., 2022; Tayyiba et al., 2021; Natasha et al., 2022; Smaoui et al., 2023) |
| Growth & development | Root architecture, leaf area, biomass, flowering, fruit set and yield | (Tayyiba et al., 2021; Jalal et al., 2024; Jan et al., 2022; Pankaj & Nirala, 2024) |
| Abiotic stress tolerance | Antioxidant defense, osmotic adjustment, membrane and photosystem protection | (Hassan et al., 2020; Jamali & Zia-Ul-Hassan, 2025; Jan et al., 2022; Hassan et al., 2022) |
| Disease & pest resistance | Immune signaling, SODs, Zn-finger proteins, reduced disease symptoms | (Han et al., 2021; Cabot et al., 2019; Pandya et al., 2023; Gondal, 2021) |

**Table 2. Effects of zinc on growth and yield of important vegetable crops**

| Crop (example study/summary) | Zn source & rate (approx.) | Main growth/yield response | Citations |
|---|---|---|---|
| Tomato | 0.5% $ZnSO_4$ foliar; 10 kg Zn $ha^{-1}$ soil; 30 ppm Zn foliar | Higher plant height, branches, fruit set, fruits $plant^{-1}$, yield up to ~50–85 t $ha^{-1}$ vs ~60–67 t $ha^{-1}$ control; earlier flowering | (Pankaj & Nirala, 2024; Ahmed et al., 2021; Yadav et al., 2023) |
| Brinjal (eggplant) | 10 mg Zn + 10 mg B per plant (foliar/soil) | Increased chlorophyll a, b, carotenoids, anthocyanin, and fruit protein; improved physiological vigor | (Pankaj & Nirala, 2024; Yadav et al., 2023) |
| Cucumber | ZnO nanoparticles 20 ppm (foliar) | Improved seed germination, plant height, leaf number/area, flowers, fruit number, fruit weight, size, firmness, and color | (Pankaj & Nirala, 2024; Ahmed et al., 2024) |
| Cauliflower | 0.5% $ZnSO_4$ + 0.5% $FeSO_4$ foliar | Highest marketable curd yield, bud diameter, bud weight, and economic return | (Pankaj & Nirala, 2024; Yadav et al., 2023) |
| Broccoli | Soil-applied B + Mn + Zn (≈3:0.5:2:2.5 kg $ha^{-1}$) | Increased bud diameter and weight, more leaves ("frouds"), higher yield $ha^{-1}$ | (Pankaj & Nirala, 2024) |
| Okra | ~7.5 kg Zn $ha^{-1}$ soil | Significantly better growth, yield, and pod quality traits | (Pankaj & Nirala, 2024; Yadav et al., 2023) |
| Onion | Soil and foliar Zn with B | Improved bulb quality (higher TSS) and yield and nutrient uptake | (Pankaj & Nirala, 2024; Yadav et al., 2023) |
| Carrot | Foliar ZnO-NPs 40 mg $L^{-1}$ (3 sprays) | Greatest shoot growth, SPAD, nutrient uptake, root length, diameter, fresh and dry yield in Zn-deficient soil | (Awad et al., 2021) |
| Spinach (hydroponic) | 5–10 mg $L^{-1}$ Zn in solution | Higher chlorophyll index, yield, protein, SOD and APX activity; lower MDA and $H_2O_2$ | (Behtash et al., 2025) |
| Pea (field) | ZnO nanoparticles up to 5 g $L^{-1}$ | Improved shoot and root traits, yield, soil microbial activity and Zn content in tissue | (Kiani et al., 2024) |

**Table 3. Effects of zinc on nutritional and biochemical quality of vegetable crops**

| Crop | Zn treatment | Key nutritional/quality improvements | Citations |
|---|---|---|---|
| Tomato | 0.5% $ZnSO_4$; 30 ppm foliar; Zn with B | Increased TSS, firmness, titratable acidity, chlorophyll a & b, vitamin C, lycopene, flavonoids, carotenoids, phenolics; higher fruit Zn | (Pankaj & Nirala, 2024; Ahmed et al., 2021; Yadav et al., 2023) |
| Cucumber | ZnO-NPs 20 ppm | Higher fruit Zn, better firmness and color, improved seed quality and early vigor | (Pankaj & Nirala, 2024; Ahmed et al., 2024) |
| Brinjal | 10 mg Zn + 10 mg B | Higher chlorophyll, carotenoids, anthocyanin, and fruit protein content | (Pankaj & Nirala, 2024) |
| Cauliflower & Broccoli | Zn (with B, Mn, Fe) soil/foliar | Better curd/head compactness, marketable quality, mineral content; improved economic quality indices | (Pankaj & Nirala, 2024; Yadav et al., 2023) |

| Crop | Zn treatment | Key nutritional/quality improvements | Citations |
|---|---|---|---|
| Okra | ~7.5 kg Zn $ha^{-1}$ soil | Improved pod quality traits; higher macro- and micronutrient content | (Pankaj & Nirala, 2024; Yadav et al., 2023) |
| Carrot | ZnO-NPs (esp. 40 mg $L^{-1}$) | Enhanced root mineral profile (P, Ca, Fe, Mn, Zn, Cu), better nutritional homeostasis | (Awad et al., 2021) |
| Pea microgreens | Zn fertigation 15 mg $L^{-1}$ $ZnSO_4$ | Zn content increased ~5-fold, plus higher flavonoids, phenols, antioxidant activity, ascorbic acid | (Poudel et al., 2024) |
| Radish & sunflower microgreens | Zn fertigation 15 mg $L^{-1}$ $ZnSO_4$ | Zn content increased up to 13-fold with increased antioxidants and ascorbic acid, minimal yield loss | (Poudel et al., 2024) |
| Brassica microgreens (arugula, red cabbage, mustard) | 5–10 mg $L^{-1}$ $ZnSO_4$ solution | Shoot Zn concentration increased 75–281% with good yield retention | (Di Gioia et al., 2019) |
| Sweet potato | Soil 2.5 kg Zn $ha^{-1}$ + foliar 15–45 ppm | Increased amino acids, β-carotene, flavonoids, phenolics, and tuber Zn content | (Rahman et al., 2024) |

## 4. Zinc Fertilization and Application Strategies

### 4.1 Zinc Fertilization Methods

#### 4.1.1 Soil Application (Basal / Banded)

Commonly applied as $ZnSO_4 \cdot 7H_2O$ at 5–25 kg $ha^{-1}$ depending on soil pH and texture (Kathula et al., 2023; Kumar et al., 2022; Regar et al., 2022; Rajendiran et al., 2024; Zeb et al., 2022). Very effective for correcting soil Zn deficiency and giving residual benefits to following crops in a rotation (Farooq et al., 2018; Kumar et al., 2022; Regar et al., 2022; Rajendiran et al., 2024). In acidic or neutral soils, $ZnSO_4$ and chelated/complexed Zn are usually more bioavailable than ZnO; in one lettuce study $ZnSO_4$ gave the highest Zn availability in year 1, with nanoparticles and complexes showing strong residual effects in year 2 (De Francisco et al., 2025).

#### 4.1.2 Foliar Spraying

Typical solutions: 0.3–1.0% $ZnSO_4$ for vegetables and pulses; 0.5% often optimal, with yield or quality declines at higher concentrations due to phytotoxicity (Hui et al., 2025; Ahmed et al., 2021; Liu et al., 2016; Ahmad et al., 2023). Particularly effective on calcareous, high-pH, Zn-fixing soils where soil-applied Zn has low efficiency, and for late correction or biofortification of edible parts (Hui et al., 2025; Ahmed et al., 2021; Hidoto et al., 2017). Foliar Zn frequently increases grain or fruit Zn concentration more than soil Zn alone and is highly effective for biofortification (Hui et al., 2025; Ahmed et al., 2021; Hidoto et al., 2017; Ahmad et al., 2023).

#### 4.1.3 Seed Priming / Coating

Seeds soaked or coated with $ZnSO_4$ or ZnO/ZnO-nanoparticles improve early vigor, root growth, and Zn content of seedlings, often with low fertilizer amounts (Tondey et al., 2021; Choukri et al., 2022; Ahmad et al., 2023; Zeb et al., 2022). In several cereals and pulses, Zn seed priming (≈0.1–0.5% $ZnSO_4$ for 8–24 h) increased yield and grain Zn, sometimes outperforming equivalent soil Zn doses in deficient soils (Choukri et al., 2022; Ahmad et al., 2023). Nano-Zn seed coating at 20–40 mg $L^{-1}$ improved vegetative growth, biomass and Zn uptake at very low application rates; higher doses risk toxicity (Tondey et al., 2021).

#### 4.1.4 Relative Effectiveness by Condition

The effectiveness of zinc (Zn) fertilization strategies varies depending on soil characteristics and crop growth conditions. In soils with low to moderate pH and evident Zn deficiency, soil application of Zn at rates of 5–15 kg ha⁻¹ has been reported to be highly effective in improving crop productivity and Zn availability, often providing residual benefits for subsequent crops (Farooq et al., 2018; Kumar et al., 2022; Regar et al., 2022; Rajendiran et al., 2024; Zeb et al., 2022). However, in calcareous or high pH soils, where Zn availability is restricted due to fixation and reduced solubility, combined soil and foliar Zn application, or foliar application alone, has been shown to enhance Zn uptake and biofortification more effectively than sole soil application (Hui et al., 2025; Ahmed et al., 2021; Hidoto et al., 2017; Ashraf et al., 2025; Ahmad et al., 2023). Under conditions of seedling stress and in low-input production systems, Zn seed priming or coating represents a cost-effective and low-dose strategy to improve germination, early seedling vigor, and crop establishment (Tondey et al., 2021; Choukri et al., 2022; Ahmad et al., 2023; Zeb et al., 2022).

## 4.2 Optimal Zinc Levels and Practical Rates

Recommended zinc (Zn) fertilization rates reported in the literature are largely derived from cereal-, pulse-, and vegetable-based production systems and are often adapted for vegetable cultivation under comparable soil conditions. Soil application of Zn, commonly in the form of $ZnSO_4 \cdot 7H_2O$, at rates of 5–10 kg Zn $ha^{-1}$ has been found effective in many neutral to slightly alkaline soils, particularly in rice–maize cropping systems, where it improves Zn availability and crop productivity (Kumar et al., 2022; Regar et al., 2022; Rajendiran et al., 2024). In some cases, a single soil application of 10 kg Zn $ha^{-1}$ increased soil DTPA-extractable Zn from deficient levels (~0.9 mg $kg^{-1}$) to adequate concentrations exceeding 1.5 mg $kg^{-1}$, thereby sustaining productivity in chilli–millet–leafy vegetable systems without the need for further Zn inputs until soil Zn levels declined again (Rajendiran et al., 2024). In highly sodic or strongly alkaline soils, higher one-time application rates of up to 22 kg Zn $ha^{-1}$ may be recommended, while long-term maize–wheat systems have shown that periodic applications of 5–10 kg Zn $ha^{-1}$ every year or in alternate years can optimize both yield and soil Zn status (Kumar et al., 2022).

Foliar Zn application is another widely adopted strategy to correct Zn deficiency, particularly when soil availability is limited. Foliar sprays of $ZnSO_4$ at concentrations of 0.3–0.5%, applied one to three times during critical growth stages such as flowering or early pod and fruit formation, have been reported to enhance yield and quality in several crops. A concentration of 0.5% $ZnSO_4$ has frequently been associated with maximum yield response in chickpea and other legumes (Hui et al., 2025; Goodarzi et al., 2025; Choudhary et al., 2025; Liu et al., 2016). However, excessive foliar concentrations (≥0.4–0.5% in sensitive crops) or an increased number of sprays may lead to phytotoxic effects such as leaf burn and growth suppression (Hui et al., 2025; Ahmed et al., 2021; Liu et al., 2016).

Seed priming or coating with Zn represents a cost-effective and low-dose approach to improve germination, early seedling vigor, and Zn enrichment in crops. Priming with 0.1–0.5% $ZnSO_4$ for 8–24 hours or applying low-dose coatings such as 20–40 mg $L^{-1}$ ZnO nanoparticles has been shown to enhance yield and grain Zn content. Nevertheless, higher concentrations (>0.5–1%) or prolonged soaking durations may increase the risk of reduced germination or Zn toxicity in certain pulse crops (Tondey et al., 2021; Choukri et al., 2022; Ahmad et al., 2023).

Given the variability in crop species and soil characteristics, soil testing remains essential for effective Zn management. Parameters such as DTPA-extractable Zn, soil pH, and texture should guide fertilization strategies. Many cropping systems aim to maintain soil DTPA-Zn levels within the adequate range of approximately 1.0–1.5 mg $kg^{-1}$, avoiding additional Zn application until concentrations decline below this threshold (Kumar et al., 2022; Rajendiran et al., 2024; Stuckey et al., 2022).

## 4.3 Toxicity Thresholds, Risk Factors, and Management Strategies for Zinc Over-Fertilization

Although zinc (Zn) is an essential micronutrient, the margin between deficiency and toxicity in plants is relatively narrow. Excessive Zn accumulation in soils can lead to phytotoxic effects and potential dietary risks. For instance, in lettuce cultivation, soil application rates of Zn ≥30 mg $kg^{-1}$ supplied through ZnO nanoparticles, Zn complexes, or $ZnSO_4$ resulted in clear toxicity symptoms and dietary health risk indices exceeding safe limits (De Francisco et al., 2025). Similarly, in perennial ryegrass, plant growth declined markedly at extremely high soil DTPA-extractable Zn concentrations (>~489 mg $kg^{-1}$), demonstrating toxicity even in Andisols that are generally considered tolerant to elevated Zn levels (Stuckey et al., 2022). Physiologically, excessive Zn disrupts plant metabolism by inducing oxidative stress, impairing root growth, and causing chlorosis, while also interfering with the uptake and balance of other essential nutrients such as iron (Fe), manganese (Mn), copper (Cu), and phosphorus (P) (Ahmed et al., 2021; Kaur & Garg, 2021).

Several agronomic practices can increase the risk of Zn over-fertilization and subsequent accumulation in soils and edible plant parts. Repeated application of high soil Zn doses in already Zn-sufficient soils, irrigation with Zn-rich wastewater, and excessive use of nano-Zn fertilizers have been identified as major contributing factors to Zn buildup in agricultural systems (De Francisco et al., 2025; Tondey et al., 2021; Akhtar et al., 2025; Kaur & Garg, 2021). Long-term wastewater irrigation, in particular, has been shown to increase both soil Zn concentrations and enrichment indices in vegetables, indicating moderate to high levels of soil contamination, even when current dietary risk indices remain below acute health risk thresholds (Akhtar et al., 2025).

To minimize the risk of Zn toxicity while maintaining adequate plant nutrition, several management strategies are recommended. First, Zn fertilization rates should be based on soil testing, taking into account initial DTPA-extractable Zn levels, soil pH, and texture. Routine application of high Zn doses should be avoided when soil Zn concentrations are already within the adequate range of approximately 1.0–1.5 mg $kg^{-1}$ (Kumar et al., 2022; Rajendiran et al., 2024; Stuckey et al., 2022). Second, moderate and crop-specific fertilization strategies should be adopted, such as soil application of 5–10 kg Zn $ha^{-1}$ in deficient soils, foliar sprays of 0.3–0.5% $ZnSO_4$ at limited frequencies, and the cautious use of low-dose nano-Zn or seed priming approaches only where justified (Regar et al., 2022; Tondey et al., 2021; Liu et al., 2016; and Ahmad et al., 2023).

Furthermore, integrated and rotational Zn management strategies are preferable to frequent high-dose applications. One-time or alternate-year soil Zn fertilization combined with occasional foliar sprays has been shown to maintain crop productivity and soil Zn balance more effectively than annual heavy applications (Farooq et al., 2018; Kumar et al., 2022; Regar et al., 2022; Rajendiran et al., 2024; Ashraf et al., 2025). Continuous monitoring of plant growth, tissue nutrient status, and yield responses is also essential, particularly when unexplained chlorosis or growth suppression occurs after Zn application, which may indicate emerging toxicity (De Francisco et al., 2025; Ahmed et al., 2021; Stuckey et al., 2022; Kaur & Garg, 2021). Finally, controlling non-fertilizer sources of Zn, such as long-term wastewater irrigation and industrial contamination, is critical to preventing chronic Zn accumulation in vegetable production systems (Akhtar et al., 2025; Kaur & Garg, 2021).

## 5. Biofortification: Zinc's Role in Improving the Nutritional Quality of Vegetables

Zinc (Zn) biofortification aims to enhance both the concentration and bioavailability of Zn in edible plant parts through integrated agronomic and genetic interventions. This approach has gained significant attention as a sustainable strategy to address micronutrient malnutrition and improve nutritional security in diverse cropping systems (Bandara & Dissanayaka, 2024; Rana et al., 2024; and Matumba et al., 2025).

Among the available approaches, agronomic biofortification through fertilizer management is considered the most immediate and widely applicable strategy for vegetable and field crops. Key methods include soil and foliar Zn fertilization using sources such as $ZnSO_4$, Zn-EDTA, ZnO, and nano-Zn formulations. These practices are typically tailored to soil Zn status, soil reaction (pH), and crop demand, and are often integrated with organic amendments or beneficial microbial inoculants to enhance Zn solubility, root uptake, and translocation to edible plant parts (Cakmak & Kutman, 2018; Bandara & Dissanayaka, 2024; and Silva et al., 2025).

In controlled or protected cultivation systems, fertigation has emerged as an effective biofortification technique, particularly for microgreens and leafy vegetables. Supplying Zn-enriched nutrient solutions through irrigation enables precise nutrient delivery and improved Zn accumulation in edible tissues. For example, fertigation with 15 mg $L^{-1}$ $ZnSO_4$ in pea, radish, and sunflower microgreens increased Zn concentrations by approximately five-, thirteen-, and six-fold, respectively, while maintaining minimal yield reduction and enhancing antioxidant attributes (Poudel et al., 2024). In addition, microbial biofortification using Zn-solubilizing microorganisms and plant growth-promoting rhizobacteria has been shown to improve root Zn uptake and translocation, with reports indicating up to fourfold increases in grain Zn concentration in cereal crops (Hussain et al., 2022).

Overall, agronomic biofortification is regarded as a rapid, cost-effective, and scalable intervention that can be readily integrated into existing vegetable-based and mixed cropping systems. Importantly, it complements genetic biofortification by ensuring adequate plant-available Zn in soils, thereby supporting the expression of high-Zn traits in improved crop cultivars (Rana et al., 2024; and Matumba et al., 2025).

### 5.1 Genetic and Breeding Approaches

Genetic biofortification focuses on developing crop cultivars with an inherently higher capacity to accumulate zinc (Zn) in edible plant tissues. This approach complements agronomic interventions and is increasingly recognized as a sustainable strategy for improving dietary Zn intake and addressing micronutrient malnutrition (Praharaj et al., 2021; Lowe et al., 2024; Stangoulis & Knez, 2022; Huertas et al., 2023; Matumba et al., 2025). Conventional plant breeding remains a primary method for Zn biofortification. It involves the identification and selection of genotypes that exhibit superior Zn uptake efficiency, root acquisition ability, and enhanced translocation of Zn to edible parts. These traits are subsequently incorporated into high-yielding and locally adapted cultivars through systematic crossing and selection programs (Praharaj et al., 2021; Lowe et al., 2024; Stangoulis & Knez, 2022; Huertas et al., 2023; Matumba et al., 2025). Advances in modern biotechnology and gene-editing techniques further support this objective by enabling targeted manipulation of genes involved in Zn transport, chelation, and storage. Such approaches aim to increase Zn loading in edible tissues while maintaining or improving overall agronomic performance and stress tolerance (Lowe et al., 2024; Stangoulis & Knez, 2022; Huertas et al., 2022; Matumba et al., 2025).

An important advantage of genetically biofortified varieties is that, once released and adopted, they can provide long-term nutritional benefits without the need for continuous fertilizer inputs. However, the successful expression of high-Zn traits still depends on adequate plant-available Zn in the soil, highlighting the complementary role of agronomic Zn management (Praharaj et al., 2021; Lowe et al., 2024; Stangoulis & Knez, 2022; Matumba et al., 2025). In vegetable crops, leafy and root vegetables—such as spinach, leafy brassicas, roots, and tubers—are particularly promising targets for Zn biofortification because they naturally accumulate relatively higher Zn concentrations than many fruit and grain crops. Moreover, these vegetables are often consumed with minimal processing, thereby enhancing the potential for improved dietary Zn intake (Younas et al., 2022; Bandara & Dissanayaka, 2024).

## 6. Health Benefits of Zinc-Enriched Vegetables

### 6.1 Addressing dietary zinc deficiency

Globally, around one-third of the population is at risk of Zn deficiency, with 60–70% of people in parts of Asia and sub-Saharan Africa vulnerable due to low Zn intake from plant-based diets and low bioavailability (Praharaj et al., 2021; Younas et al., 2022; Majumdar et al., 2025; Silva et al., 2025; Matumba et al., 2025). Zn deficiency is linked to poor growth, impaired immunity, increased infection risk, adverse pregnancy outcomes, and damage to multiple organ systems including epidermal, nervous, gastrointestinal, skeletal, immune and reproductive systems (Praharaj et al., 2021; Majumdar et al., 2025; Hussain et al., 2022; Baghaie & Khosravi-Dehkordi, 2025; Silva et al., 2025; Matumba et al., 2025).

Biofortified crops are highlighted as a sustainable, population-level intervention that raises dietary Zn intake without requiring major diet change or continuous supplementation, and are particularly suited to low-income settings (Silva et al., 2025; and Rana et al., 2024). Regular consumption of Zn-biofortified foods increases Zn absorption, improves Zn status, and reduces prevalence of Zn deficiency (Baghaie & Khosravi-Dehkordi, 2025; Tsang et al., 2021).

### 6.2 Effects on Immune, Cognitive and Overall Health

Zinc (Zn) plays a critical role in numerous physiological processes in humans, including innate and adaptive immune function, antioxidant defense mechanisms, DNA repair, and cell division. Consequently, Zn deficiency can impair immune responses and increase both the incidence and severity of infectious diseases (Praharaj et al., 2021; Majumdar et al., 2025; Hussain et al., 2022; Baghaie & Khosravi-Dehkordi, 2025; Silva et al., 2025). Evidence from systematic reviews of Zn-fortified foods primarily staple crops but mechanistically relevant to biofortified vegetables demonstrates that improved dietary Zn intake can significantly increase plasma Zn concentrations and reduce the prevalence of Zn deficiency in vulnerable populations (Baghaie & Khosravi-Dehkordi, 2025; Tsang et al., 2021). Furthermore, enhanced Zn consumption has been associated with reduced incidence of diarrhea and febrile illnesses, along with modest improvements in child growth, particularly in terms of weight gain (Baghaie & Khosravi-Dehkordi, 2025; Tsang et al., 2021). Additional benefits include positive effects on cognitive and motor development, with improvements in short-term auditory memory reported among children consuming Zn-fortified foods (Majumdar et al., 2025; Baghaie & Khosravi-Dehkordi, 2025; Tsang et al., 2021).

Vegetables represent an important dietary vehicle for Zn delivery because they provide not only Zn but also vitamins, antioxidants, and dietary fiber. Therefore, Zn-biofortified vegetables have the potential to synergistically enhance immune competence, cognitive performance, and cardiometabolic health, particularly in plant-based dietary systems where Zn intake from animal sources is limited (Younas et al., 2022; Majumdar et al., 2025; Baghaie & Khosravi-Dehkordi, 2025; Bandara & Dissanayaka, 2024; Silva et al., 2025).

## 6.3 Global Case Studies in zinc Biofortification

Although much of the existing evidence on Zn biofortification originates from cereals and legumes, recent research has demonstrated successful implementation in vegetable production systems. In controlled environment agriculture in the USA and Europe, Brassicaceae and legume microgreens grown in soilless culture with Zn-enriched nutrient solutions exhibited substantial increases in shoot Zn concentration, ranging from 75–281% in Brassicaceae species to up to 13-fold in radish, with minimal yield penalties and enhanced phytochemical profiles (Poudel et al., 2024; Di Gioia et al., 2019). These nutrient-dense microgreens are increasingly recognized as functional foods capable of delivering dietary Zn in urban and peri-urban food systems.

Similarly, studies on lettuce and other leafy vegetables in Brazil and other regions have shown that foliar Zn fertilization can significantly increase leaf Zn concentration without compromising yield, highlighting the feasibility of agronomic Zn biofortification to directly enhance Zn intake from fresh vegetables and salads (Cakmak & Kutman, 2018; Bandara & Dissanayaka, 2024; Silva et al., 2025). In Bangladesh, soil application of 8 kg Zn $ha^{-1}$ increased potato tuber Zn concentration by 56–116% and improved tuber yield by 17–23%, demonstrating that Zn biofortification strategies can simultaneously enhance crop productivity and nutritional quality in populations with high potato consumption (Ahammed et al., 2025).

Large-scale national and international biofortification initiatives, such as those targeting Fe- and Zn-dense varieties of wheat, rice, and common beans across Asia, Africa, and Latin America, provide valuable implementation models for vegetable biofortification programs. These initiatives have shown that regular consumption of biofortified staples can improve Zn biomarkers and reduce maternal and childhood morbidity, while also establishing effective seed systems, extension frameworks, and consumer acceptance strategies (Baghaie & Khosravi-Dehkordi, 2025; Lowe et al., 2024; Silva et al., 2025; Stangoulis & Knez, 2022; Huertas et al., 2023).

In regions where plant-based diets predominate and Zn deficiency is widespread, modelling studies and intervention data indicate that incorporating Zn-biofortified crops into daily diets can substantially reduce the dietary Zn gap, particularly among women and children. Such interventions therefore hold considerable potential for addressing hidden hunger and reducing nutrition-related health disparities (Stangoulis & Knez, 2022; Huertas et al., 2023; and Matumba et al., 2025).

## 6.4 Synergies between Zinc and Other Nutrients

Zinc interacts closely with both macronutrients and micronutrients. Adequate nitrogen supply generally enhances root growth and Zn uptake, and combined N–Zn fertilization can improve both Zn nutrition and N use efficiency (Kumar et al., 2021; Fan et al., 2021; Ahmed et al., 2024). In contrast, high phosphorus inputs frequently depress Zn availability and plant Zn concentration through precipitation of Zn–phosphates and competition at transport sites; excessive P fertilization is widely recognized as a driver of Zn deficiency in crops (Paramesh et al., 2020; Nadeem et al., 2024; Noulas et al., 2018). Balanced P management and the use of phospho-enriched compost rather than sole mineral P helped to alleviate P-induced Zn deficiency and increased grain Zn and Fe in wheat (Paramesh et al., 2020). Potassium interacts less specifically with Zn, but adequate K together with organic amendments and Zn fertilizer improved N and K status, chlorophyll content and Zn accumulation in wheat under alkaline conditions, indicating a positive macronutrient–Zn synergy when overall nutrition is balanced (Athar et al., 2025).

Among micronutrients, Zn and Fe share transporters and regulatory networks; cross-talk between Zn and Fe homeostasis means that Zn fertilization can also increase grain Fe, while Fe or P fertilizers can be used to mitigate excess Zn uptake in contaminated soils (Kumar et al., 2021; Fan et al., 2021; Xie et al., 2019). Interactions among N, P, S, Fe and Zn are coordinated partly by central regulators such as the transcription factor PHR1, emphasizing that deficiencies or excesses of a single nutrient reverberate through Zn uptake and partitioning (Kumar et al., 2021; Xie et al., 2019).

## 6.5 Effects of Soil pH and Organic Matter on Zinc Availability

Zinc occurs in soils in several pools (water-soluble, adsorbed, carbonate-bound, oxide-bound, organically complexed and residual) whose relative sizes and exchange rates determine phyto-availability (Saleem et al., 2022; Noulas et al., 2018; Jalal et al., 2024; Taşpinar et al., 2025). Soil pH is a dominant control: increasing pH generally enhances sorption of Zn to clay minerals, Fe/Al oxides and carbonates, thereby reducing $Zn^{2+}$ activity in soil solution and plant uptake, particularly in calcareous and alkaline soils (Saleem et al., 2022; Noulas et al., 2018; Barrow & Hartemink, 2023; Jalal et al., 2024). Conversely, in moderately acidic soils, Zn solubility and plant availability increase, though strong acidity can also mobilize competing metals and affect root physiology (Saleem et al., 2022; Adamczyk-Szabela & Wolf, 2022; Barrow & Hartemink, 2023). Detailed analyses show that while sorption of Zn rises with pH, plant uptake capacity also changes with pH; overall, a small but consistent decline in plant-available Zn with increasing pH is observed, especially for Zn-sensitive species (Barrow & Hartemink, 2023).

Organic matter has dual and context-dependent roles. On one hand, farmyard manure, compost, crop residues and bioslurry additions increase cation exchange capacity, improve soil structure, and stimulate microbial activity and root growth, all of which can enhance Zn uptake (Sreethu et al., 2024; Pradhan et al., 2025; Gondal et al., 2023; Dhilipan et al., 2024; Raza et al., 2025; Taşpinar et al., 2025). Long-term experiments across Indian Inceptisols demonstrated that substituting 50% of mineral N with FYM (50% NPK + 50% N through FYM) maintained a positive Zn balance in soil and raised Zn uptake by 39% relative to 100% NPK alone (Pradhan et al., 2025). Similarly, co-application of compost or rice husk with Zn sulfate in alkaline soils increased available Zn, N and K, improved plant growth, and raised grain Zn content by ~49% in wheat (Athar et al., 2025). In maize, combining bioslurry and compost with Zn sulfate improved soil quality indices by up to 87% and increased grain Zn by 71% compared with controls (Gondal et al., 2023).

On the other hand, in soils with very high organic matter, strong complexation of Zn by humic substances can reduce free $Zn^{2+}$ concentrations and thus its immediate availability, particularly at neutral to high pH (Saleem et al., 2022; Noulas et al., 2018; Jalal et al., 2024). Recent assessments in semiarid regions show that available Zn correlates positively with organic matter and available P at landscape scale, but the ratio of available to total Zn (Zn availability ratio) is strongly modulated by pH and carbonate content (Taşpinar et al., 2025). Thus, optimal Zn management requires simultaneous consideration of pH, carbonate status, organic matter level and competing ions.

## 6.6 Integrated Nutrient Management (INM) for Zinc Efficiency

Integrated nutrient management that combines mineral fertilizers with organic amendments and biofertilizers is consistently shown to improve Zn efficiency, crop yield and soil health compared with mineral fertilizers alone (Sreethu et al., 2024; Pradhan et al., 2025; Gondal et al., 2023; Dhilipan et al., 2024; Raza et al., 2025). Long-term experiments in multiple Indian cropping systems indicate that conjunctive application of NPK with FYM (typically 75–100% recommended NPK plus 50% of N as FYM) maintains or increases DTPA-Zn, shifts Zn into more labile fractions, and sustains higher Zn uptake and yields than 100% NPK (Pradhan et al., 2025; Raza et al., 2025). In Vertisols under maize, adding FYM, poultry manure, urban compost, green leaf manure and residue mulches with NPK increased DTPA-Zn up to 2.48 mg $kg^{-1}$ and enhanced grain Zn uptake relative to mineral fertilization alone; sorbed, Mn-oxide-bound and carbonate-bound Zn pools had the largest direct effects on plant Zn uptake (Raza et al., 2025).

At shorter timescales, pot and field experiments demonstrate that the combined use of compost, bioslurry or rice husk with Zn sulfate significantly improves Zn acquisition and growth in cereals cultivated on Zn-deficient or alkaline soils, largely by improving soil organic carbon, labile Zn fractions, and N and K availability (Gondal et al., 2023; Athar et al., 2025). Similar INM strategies in wheat, involving phospho-enriched compost plus mineral P and combined soil–foliar Zn, reduced the antagonistic effect of high mineral P on Zn, and increased both Zn and Fe concentrations in grain without sacrificing yield (Paramesh et al., 2020).

Beyond organic manures, biofertilizers and Zn-solubilizing bacteria further enhance Zn efficiency. Recent INM trials in wheat using Azotobacter, phosphate-solubilizing and Zn-solubilizing bacteria, together with balanced NPK and Zn fertilization, improved tillering, Zn uptake and soil exchangeable Zn, while organic manure additions were identified as essential for sustaining soil quality and crop productivity (Sreethu et al., 2024). Broader reviews of cross-talks between macro- and micronutrients suggest that combined N and Zn fertilization, together with appropriate P and Fe management, is a promising field strategy for simultaneously enhancing N and Zn nutrition and minimizing nutrient antagonisms, particularly in high-pH, Zn-deficient soils (Kumar et al., 2021; Fan et al., 2021; Xie et al., 2019).

Collectively, these studies indicate that Zn efficiency is maximized under systems where: (i) mineral NPK are applied at balanced, crop-responsive rates; (ii) substantial organic inputs (FYM, compost, bioslurry, crop residues) maintain soil organic carbon and labile Zn pools; (iii) Zn fertilizers are applied in forms and placements suited to soil pH and texture; and (iv) microbial inoculants and crop rotations are used to enhance root uptake and minimize fixation. Such integrated approaches improve the synchronization between Zn and other nutrients in soil–plant systems and provide a foundation for sustainable, Zn-efficient agriculture.

## 7. Sustainable Zinc Management Practices

Slow- and controlled-release fertilizers are promoted to increase micronutrient use efficiency and reduce losses from leaching, runoff and volatilization (Priya et al., 2024). Coated and nano-enabled formulations can synchronize Zn release with crop demand, prolong residence time in the root zone, and limit environmental contamination (Saleem et al., 2022; Beig et al., 2023; Shoukat et al., 2025; Priya et al., 2024). For example, urea coated with ZnO nanoparticles and molasses (slow-release N–Zn fertilizer) reduced N and Zn release rates, improved N and Zn uptake, and increased wheat yield by 34% relative to conventional urea (Beig et al., 2023). Nano-Zn formulations applied alone or with silicon improved maize grain yield and nutrient-use efficiency under saline and non-saline conditions, illustrating their value under stress-prone climates (Shoukat et al., 2025).

Organic amendments such as manures, composts and biochar are central to sustainable Zn fertilization because they supply Zn, increase cation exchange capacity and water-holding capacity, and stimulate microbial activity that mobilizes Zn (Baghaie & Khosravi-Dehkordi, 2025; Sreethu et al., 2024; Noulas et al., 2018; Manzeke-Kangara et al., 2021; Ahmed et al., 2024). Combining Zn fertilizers with locally available organic resources and optimal NPK substantially increased maize grain Zn in Zimbabwe and markedly reduced modeled dietary Zn deficiency, demonstrating the public-health relevance of soil-based Zn management (Noulas et al., 2018). Integration of Zn nanoparticles with biochar can further provide slow Zn release, enhanced Zn bioavailability, and improved soil structure, though potential ecotoxicological risks require careful assessment (Manzeke-Kangara et al., 2021).

Precision fertilization technologies using GIS, GPS, remote sensing, IoT and AI enable site-specific Zn management by mapping intra-field variability and applying variable Zn rates only where needed, reducing over-application and nutrient runoff while sustaining yields (Hou et al., 2025; Liu et al., 2025; Bhamini et al., 2025; Polwaththa et al., 2024). These tools support data-driven recommendations, real-time diagnosis of Zn deficiency, and integration of nano- and slow-release Zn sources into smart fertilization systems (Hou et al., 2025; Liu et al., 2025; Bhamini et al., 2025; Polwaththa et al., 2024).

### 7.1 Soil Health and Conservation Practices

Long-term soil health is a prerequisite for sustained Zn availability. Continuous monocropping, intensive tillage and reliance on mineral fertilizers alone degrade soil structure, reduce organic matter, and impair micronutrient cycling (Manzeke-Kangara et al., 2021; Khan et al., 2024; Țopa et al., 2025; Omer et al., 2024). Conservation agriculture practices—reduced or no tillage, residue retention, cover cropping and diversified rotations—tend to increase soil organic carbon, improve aggregation and water retention, and foster diverse microbial communities that mobilize Zn and other micronutrients (Khan et al., 2024; Țopa et al., 2025; Meena et al., 2023; Omer et al., 2024).

Crop rotation and organic farming systems can enhance Zn concentration and bioavailability in cereals. In a long-term Canadian rotation experiment, organic management and diversified annual–perennial rotations significantly increased wheat grain Zn and reduced phytate/Zn ratios, improving estimated Zn bioavailability for humans, albeit sometimes at the cost of lower yields due to P limitation (Hou et al., 2025). At field scale, combining mineral NPK with organic amendments and good soil management in Zimbabwe increased maize grain Zn and was projected to sharply reduce national dietary Zn deficiency and associated disability-adjusted life years (Noulas et al., 2018).

Integrated nutrient management that blends organic and inorganic inputs with biofertilizers improves soil physical, chemical and biological properties and maintains labile Zn pools, thereby supporting both productivity and long-term Zn supply (Baghaie & Khosravi-Dehkordi, 2025; Sreethu et al., 2024; Cakmak & Kutman, 2018; Meena et al., 2023). Conservation tillage with balanced nutrient inputs in semi-arid Vertisols increased soil organic C and several available nutrients, and Zn availability emerged as a key indicator of soil health in soybean–wheat systems (Meena et al., 2023).

### 7.2 Impact of Climate Change on Zinc Availability

Climate change is expected to alter Zn dynamics through shifts in temperature, precipitation patterns, evapotranspiration and extreme events. Increased frequency of droughts reduces soil moisture, which is critical for diffusion-driven Zn transport to roots; reduced moisture is already associated with impaired Zn uptake and more frequent Zn deficiency in semi-arid cereal systems (Manzeke-Kangara et al., 2021; Cakmak & Kutman, 2018). Heat and water stress can also modify root growth, exudation of organic ligands, and mycorrhizal associations, thereby influencing Zn acquisition efficiency (Saleem et al., 2022; Manzeke-Kangara et al., 2021).

Salinization of irrigated lands projected to worsen with sea-level rise, higher evaporative demand and poor-quality irrigation water adversely affects Zn nutrition by ionic competition, osmotic stress and altered rhizosphere chemistry (Saleem et al., 2022; Shoukat et al., 2025). Under such saline field conditions, nano-Zn and nano-Si fertilizers improved maize nutrient-use efficiency, reduced Na accumulation and increased grain yield by up to 106% compared with unfertilized controls, indicating that advanced Zn formulations can partially buffer climate-driven salinity impacts (Shoukat et al., 2025).

Warmer temperatures and elevated $CO_2$ may also change soil organic matter turnover and redox conditions, with complex consequences for Zn sorption–desorption equilibria and transport in soil–water systems (Manzeke-Kangara et al., 2021; Kumar et al., 2022). In many regions, intensified rainfall and erosion will deplete topsoil organic matter and fine particles that store Zn, further lowering the Zn-supplying power of soils unless conservation measures are adopted (Manzeke-Kangara et al., 2021; Khan et al., 2024; Țopa et al., 2025).

Consequently, climate-resilient Zn management must couple adaptation and mitigation strategies: enhancing soil organic carbon through organic amendments and reduced tillage; adopting drought- and salinity-tolerant, Zn-efficient crop genotypes; using slow-release and nano-Zn fertilizers tailored to stress-prone environments; and deploying precision agriculture tools to dynamically adjust Zn inputs in response to weather variability and soil conditions (Hou et al., 2025; Khan et al., 2024; and Cakmak & Kutman, 2018).

## 8. Future Directions in Zinc Research for Vegetable Crops

Emerging Zn fertilizers, particularly nano-enabled formulations, are a central future direction. Nanofertilizers based on zinc oxide nanoparticles (ZnO-NPs) offer controlled and targeted release, higher surface area, and improved mobility in plant tissues, which can increase Zn use efficiency relative to bulk Zn salts (Tondey et al., 2021; Saleem et al., 2022; Beig et al., 2023). Seed priming or coating with ZnO-NPs has been shown to improve early growth, biomass, yield components, and shoot Zn content in maize, while also stimulating soil microbial activity and enzyme function, indicating potential as a delivery system for micronutrients in field crops and, by extension, vegetable systems (Tondey et al., 2021). Foliar application of ZnO-NPs in tomato enhances plant height, earliness, yield, and quality traits such as lycopene, total soluble solids, and ascorbic acid, highlighting the promise of nano-Zn fertilizers to improve both productivity and nutritional value in vegetable crops (Ahmed et al., 2021). Future research is likely to focus on optimizing particle size, concentration and application timing, developing hybrid nano-coatings that combine Zn with N or other nutrients, and assessing long-term environmental and food safety impacts of nano-Zn in vegetable production (Saleem et al., 2022; Beig et al., 2023).

Breeding for Zn-efficient and Zn-dense varieties represents another major frontier. Zn efficiency defined as the capacity to sustain growth and yield under low Zn supply relies on traits such as enhanced root surface area, secretion of Zn-mobilizing exudates, and more effective cellular Zn utilization (Hacisalihoglu, 2020). Considerable natural variation for Zn efficiency and seed/tissue Zn concentration has been documented in several crops, and these traits can be exploited for biofortification, including in vegetables (Hacisalihoglu, 2020; Cakmak & Kutman, 2018). Modern approaches include quantitative trait loci (QTL) mapping and genome-wide association studies (GWAS) to identify loci and candidate genes involved in Zn uptake, transport and allocation; for example, recent GWAS in common bean identified loci linked to root-to-seed Zn allocation and candidate genes such as vacuolar iron transporter 1 and wall-associated kinase-like proteins that modulate Zn homeostasis. Such studies, together with meta-QTL analyses in cereals, illustrate how precise genomic regions and superior haplotypes can be defined for marker-assisted selection and genomic selection aimed at higher grain or seed Zn. Future directions emphasized for Zn-efficient crops include identifying key genes and pathways controlling Zn efficiency, using genome editing tools such as CRISPR-Cas9, conducting metabolomic profiling of Zn-efficiency responses, and integrating GWAS/QTL information into breeding pipelines to develop Zn-dense, stress-tolerant vegetable cultivars (Hacisalihoglu, 2020; Cakmak & Kutman, 2018). Transgenic and gene-editing strategies that up-regulate Zn transporters, chelators, or reduce anti-nutritional factors such as phytic acid also offer powerful routes to enhance Zn content and bioavailability in edible organs (Shoukat et al., 2025).

Technological advances in Zn monitoring and management are expected to further transform Zn nutrition in vegetable systems. Precision agriculture platforms that couple Internet of Things (IoT) soil and plant sensors with artificial intelligence (AI) and machine learning can provide real-time measurements of soil moisture, nutrient status (including Zn proxies), and plant performance, enabling site- and time-specific Zn fertilizer recommendations. Recent AI-driven smart agriculture systems integrate sensor data with deep-learning models to optimize fertilizer regimes and irrigation, achieving highly accurate predictions for soil properties, crop choice, and fertilizer type and dose. Similar frameworks, extended with high-throughput phenotyping and spectral imaging, can be used to detect Zn deficiency symptoms, estimate tissue Zn status remotely, and adjust Zn fertilization dynamically in vegetable fields and greenhouses. As nano-Zn and advanced controlled-release fertilizers are adopted, integrating their behavior into decision-support models will be crucial for avoiding over-application and minimizing environmental risks (Saleem et al., 2022; Beig et al., 2023).

Overall, future research on Zn in vegetable crops will likely converge on three priorities: (i) designing safe, efficient nano- and smart Zn fertilizers tailored to vegetable production systems; (ii) breeding and engineering Zn-efficient, nutrient-dense vegetable varieties using genomics, GWAS, and genome editing; and (iii) deploying sensor- and AI-based precision tools to monitor Zn status and optimize inputs in real time, thereby closing the gap between genetic potential, agronomic management, and human Zn nutrition.

## 9. Conclusion

Zinc is a crucial micronutrient that plays an essential role in the growth, productivity, and quality of vegetable crops. It is involved in various key plant functions, such as enzyme activation, protein synthesis, and chlorophyll production, which are vital for healthy plant growth. Zinc also contributes significantly to improving plants' resilience to both biotic and abiotic stresses, including drought and heat, which are increasingly prevalent due to climate change. Additionally, zinc impacts the development of roots and flowers, which in turn affects fruit set and overall yield. Its role in enhancing the nutritional quality of vegetables is also noteworthy, as it improves the micronutrient content of the crops, which is essential for human health. In regions where zinc deficiency is widespread, optimizing zinc availability in soil can substantially improve both the yield and nutritional value of vegetable crops, thus contributing to food security and improved public health.

## 10. Recommendations for Agricultural Practices

To maximize the benefits of zinc in vegetable farming, it is critical to adopt several best practices for efficient zinc use. One key strategy is to implement optimized zinc fertilization by conducting regular soil tests to assess zinc levels and applying fertilizers accordingly. Different zinc formulations, such as nano-zinc or slow-release fertilizers, can be used to enhance the bioavailability of zinc and reduce the risk of overuse. In addition, foliar application of zinc during critical growth stages can provide quick corrections for zinc deficiencies, leading to improved plant health and higher yields. Another important practice is integrated nutrient management (INM), where zinc is supplemented alongside other essential nutrients to ensure balanced and efficient nutrient uptake. Zinc biofortification is also a promising approach to enhance the zinc content of vegetables, particularly in regions with widespread micronutrient deficiencies. Moreover, sustainable soil health management practices, including crop rotation, reduced tillage, and organic farming, should be adopted to prevent zinc depletion in the soil and to enhance its long-term availability to plants.

## 11. Further Research and Policy Action

Although substantial progress has been made in understanding the importance of zinc in agriculture, further research is needed to explore and optimize its use in vegetable crops. Developing zinc-efficient crop varieties, particularly those that can thrive in zinc-deficient soils, should be a priority for researchers. Additionally, exploring the potential of nano-zinc fertilizers and understanding their long-term effects on both crop yield and soil health could provide valuable insights for improving zinc efficiency. It is also essential to investigate how zinc supplementation can help crops withstand the impacts of climate change, such as increasing temperatures and water scarcity, which present new challenges to agricultural productivity. On a policy level, governments and agricultural institutions should support initiatives that promote sustainable zinc management practices, including the development and adoption of zinc-efficient technologies. Such policies would incentivize farmers to use innovative fertilization strategies and improve overall agricultural sustainability.

## 12. Global Implications

Addressing zinc deficiency is of utmost importance for both food security and human health on a global scale. Zinc is not only essential for plant growth but also plays a vital role in human nutrition, particularly in preventing micronutrient malnutrition. In regions where zinc deficiency is wide spread, targeted interventions to improve soil zinc levels can significantly boost vegetable crop yields and enhance their nutritional quality, which is vital for combating malnutrition. Furthermore, as the world faces increasing challenges related to climate change, optimizing zinc use in agriculture can contribute to building resilient food systems. Sustainable zinc management practices will ensure that crops remain healthy and productive, while minimizing the environmental impact of excessive fertilizer use. By integrating zinc management into broader agricultural strategies, we can address pressing nutritional challenges and promote the long-term sustainability of agricultural systems, ensuring that future generations have access to healthy, nutrient-rich food.

## Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

## Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

A., S., A., S., & N, M. (2020). Role of zinc nutrition for increasing zinc availability, uptake, yield, and quality of maize (*Zea mays* L.) grains: An overview. *Communications in Soil Science and Plant Analysis, 51*, 2001–2021. https://doi.org/10.1080/00103624.2020.1820030

Abedi, T., Gavanji, S., & Mojiri, A. (2022). Lead and zinc uptake and toxicity in maize and their management. *Plants, 11*. https://doi.org/10.3390/plants11151922

Adamczyk-Szabela, D., & Wolf, W. (2022). The impact of soil pH on heavy metals uptake and photosynthesis efficiency in *Melissa officinalis, Taraxacum officinalis, Ocimum basilicum*. *Molecules, 27*. https://doi.org/10.3390/molecules27154671

Ahammed, S., Rahim, M., & Hossain, M. (2025). Biofortification of potato tubers with zinc fertilizer through soil. *Asian Plant Research Journal*. https://doi.org/10.9734/aprj/2025/v13i1290

Ahmad, W., Zou, Z., Awais, M., Munsif, F., Khan, A., Nepal, J., Ahmad, M., Akbar, S., Ahmad, I., Khan, M., Qamar, Z., & Khan, H. (2023). Seed-primed and foliar oxozinc nanofiber application increased wheat production and Zn biofortification in calcareous-alkaline soil. *Agronomy*. https://doi.org/10.3390/agronomy13020400

Ahmed, N., Deng, L., Narejo, M., Baloch, I., Deng, L., Chachar, S., Li, Y., Li, J., Bozdar, B., Chachar, Z., Hayat, F., Chachar, M., Gong, L., & Tu, P. (2024). Bridging agro-science and human nutrition: Zinc nanoparticles and biochar as catalysts for enhanced crop productivity and biofortification. *Frontiers in Plant Science, 15*. https://doi.org/10.3389/fpls.2024.1435086

Ahmed, R., Samad, M., Uddin, M., Quddus, M., & Hossain, M. (2021). Recent trends in the foliar spraying of zinc nutrient and zinc oxide nanoparticles in tomato production. *Agronomy*. https://doi.org/10.3390/agronomy11102074

Akhtar, S., Muneeb, A., Khan, Z., Saba, I., Ahmad, K., Faisal, M., Alatar, A., Hussain, I., Zubair, R., & Nadeem, M. (2025). Long term urban wastewater irrigation drives zinc bioaccumulation and health risks in contaminated vegetables. *Scientific Reports, 15*. https://doi.org/10.1038/s41598-025-06026-5

Ashraf, M., Qamar, F., Mehran, M., Masood, S., Shahzad, S., Javed, M., & Azhar, M. (2025). Zinc nutrition optimization for better cotton productivity on alkaline calcareous soil. *Journal of Cotton Research, 8*. https://doi.org/10.1186/s42397-025-00218-0

Athar, M., Fatima, S., Zahra, A., Shah, M., Bashir, S., Seleiman, M., & Ali, N. (2025). Optimizing wheat growth and zinc uptake with compost and rice husk in alkaline conditions. *BMC Plant Biology, 25*. https://doi.org/10.1186/s12870-025-06537-3

Awad, A., Rady, M., Semida, W., Belal, E., Omran, W., Al-Yasi, H., & Ali, E. (2021). Foliar nourishment with different zinc-containing forms effectively sustains carrot performance in zinc-deficient soil. *Agronomy*. https://doi.org/10.3390/agronomy11091853

Baghaie, A., & Khosravi-Dehkordi, A. (2025). The critical role of zinc in improving public health and crop quality: Examining challenges and strategies for soil enrichment in developing countries. *International Journal of Environmental Health Engineering*. https://doi.org/10.4103/ijehe.ijehe_62_24

Bandara, R., & Dissanayaka, D. (2024). Agronomic biofortification of vegetables to achieve iron and zinc nutritional security in food systems. *Journal of Plant Nutrition, 48*, 974–994. https://doi.org/10.1080/01904167.2024.2416075

Barrow, N., & Hartemink, A. (2023). The effects of pH on nutrient availability depend on both soils and plants. *Plant and Soil*, 1–17. https://doi.org/10.1007/s11104-023-05960-5

Behtash, F., Ramezani, R., Hajizadeh, H., & Eghlima, G. (2025). Optimum concentrations of potassium and zinc for better performance, nutritional, and biochemical quality of hydroponically cultivated *Spinacia oleracea* cv. Virofly. *Scientific Reports, 15*. https://doi.org/10.1038/s41598-025-96911-w

Beig, B., Niazi, M., Jahan, Z., Haider, G., Zia, M., Shah, G., Iqbal, Z., & Hayat, A. (2023). Development and testing of zinc sulfate and zinc oxide nanoparticle-coated urea fertilizer to improve N and Zn use efficiency. *Frontiers in Plant Science, 13*. https://doi.org/10.3389/fpls.2022.1058219

Bhamini, K., Kumar, A., Magrey, A., Jafri, S., Najmusaqib, S., L, P., R., & Jan, I. (2025). The role of GIS and GPS in precision fertilization: Optimizing nutrient management for sustainable cropping. *International Journal of Research in Agronomy*. https://doi.org/10.33545/2618060x.2025.v8.i2d.2574

Bhatt, R., Hossain, A., & Sharma, P. (2020). Zinc biofortification as an innovative technology to alleviate the zinc deficiency in human health: A review. *Open Agriculture, 5*, 176–187. https://doi.org/10.1515/opag-2020-0018

Cabot, C., Martos, S., Llugany, M., Gallego, B., Tolrà, R., & Poschenrieder, C. (2019). A role for zinc in plant defense against pathogens and herbivores. *Frontiers in Plant Science, 10*. https://doi.org/10.3389/fpls.2019.01171

Cakmak, I., & Kutman, U. (2018). Agronomic biofortification of cereals with zinc: A review. *European Journal of Soil Science, 69*. https://doi.org/10.1111/ejss.12437

Choudhary, K., Bhinda, N., Sharma, D., Kumar, R., Dayma, J., & Yadav, D. (2025). Effect of soil and foliar application of zinc on yield attributes and yield of chickpea (*Cicer arietinum* L.). *International Journal of Environment, Agriculture and Biotechnology*. https://doi.org/10.22161/ijeab.104.21

Choukri, M., Abouabdillah, A., Bouabid, R., Abd-Elkader, O., Pacioglu, O., Boufahja, F., & Bourioug, M. (2022). Zn application through seed priming improves productivity and grain nutritional quality of silage corn. *Saudi Journal of Biological Sciences, 29*. https://doi.org/10.1016/j.sjbs.2022.103456

De Francisco, M., Ortiz, R., Obrador, A., González, D., Gascó, G., & Almendros, P. (2025). The effect of complexed, nanosized, and conventional zinc sources applied at varying rates to an acidic Mediterranean soil on two successive lettuce crops. *Agronomy*. https://doi.org/10.3390/agronomy15040896

Dhilipan, K., Baradhan, G., Kumar, S., Sathiyanarayanan, G., & Ramesh, S. (2024). Evaluating the synergistic effects of integrated nutrient management and foliar application of zinc sulphate ($ZnSO_4$) on growth and growth attributes of rice (*Oryza sativa* L.). *Crop Research*. https://doi.org/10.31830/2454-1761.2024.cr-975

Di Gioia, F., Petropoulos, S., Ozores-Hampton, M., Morgan, K., & Rosskopf, E. (2019). Zinc and iron agronomic biofortification of Brassicaceae microgreens. *Agronomy*. https://doi.org/10.3390/agronomy9110677

Fan, X., Zhou, X., Chen, H., Tang, M., & Xie, X. (2021). Cross-talks between macro- and micronutrient uptake and signaling in plants. *Frontiers in Plant Science, 12*. https://doi.org/10.3389/fpls.2021.663477

Farooq, M., Ullah, A., Rehman, A., Nawaz, A., Nadeem, A., Wakeel, A., Nadeem, F., & Siddique, K. (2018). Application of zinc improves the productivity and biofortification of fine grain aromatic rice grown in dry seeded and puddled transplanted production systems. *Field Crops Research, 216*, 53–62. https://doi.org/10.1016/j.fcr.2017.11.004

Gondal, A. (2021). A detailed review study of zinc involvement in animal, plant and human nutrition. **, 9*, 262–271. https://doi.org/10.18782/2582-2845.8652

Gondal, A., Khan, M., Cheema, S., Hussain, M., Ali, B., Nawaz, M., Dawood, M., & Murtaza, G. (2023). The co-application of bioslurry and compost with inorganic zinc fertilizer improved soil quality, zinc uptake, and growth of maize crop. *Arabian Journal of Geosciences, 16*. https://doi.org/10.1007/s12517-023-11503-0

Goodarzi, S., Tavanmand, A., & Shajari, H. (2025). Effect of different concentration and application method of zinc on yield of chickpea (*Pisum sativum* L.). *American Journal of Biomedical Science & Research*. https://doi.org/10.34297/ajbsr.2025.25.003346

Hacisalihoglu, G. (2020). Zinc (Zn): The last nutrient in the alphabet and shedding light on Zn efficiency for the future of crop production under suboptimal Zn. *Plants, 9*. https://doi.org/10.3390/plants9111471

Hafeez, B., Khanif, Y., & Saleem, M. (2013). Role of zinc in plant nutrition: A review. *American Journal of Experimental Agriculture, 3*, 374–391. https://doi.org/10.9734/ajea/2013/2746

Han, G., Qiao, Z., Li, Y., Wang, C., & Wang, B. (2021). The roles of CCCH zinc-finger proteins in plant abiotic stress tolerance. *International Journal of Molecular Sciences, 22*. https://doi.org/10.3390/ijms22158327

Hassan, M., Aamer, M., Chattha, M., Tang, H., Shahzad, B., Barbanti, L., Nawaz, M., Rasheed, A., Afzal, A., Liu, Y., & Huang, G. (2020). The critical role of zinc in plants facing the drought stress. *Agriculture*. https://doi.org/10.3390/agriculture10090396

Hassan, M., Nawaz, M., Mahmood, A., Shah, A., Shah, A., Muhammad, F., Batool, M., Rasheed, A., Jaremko, M., Abdelsalam, N., Hasan, M., & Qari, S. (2022). The role of zinc to mitigate heavy metals toxicity in crops. **, 10*. https://doi.org/10.3389/fenvs.2022.990223

Hidoto, L., Worku, W., Mohammed, H., & Bunyamin, T. (2017). Effects of zinc application strategy on zinc content and productivity of chickpea grown under zinc deficient soils. *Journal of Soil Science and Plant Nutrition, 17*, 112–126. https://doi.org/10.4067/s0718-95162017005000009

Hosamani, V., Yalagi, M., Sasvihalli, P., Hosamani, V., Nair, K., Harlapur, V., Hegde, C., & Mishra, R. (2020). Importance of micronutrients (zinc) in crop production: A review. *International Journal of Chemical Studies, 8*, 1060–1064. https://doi.org/10.22271/chemi.2020.v8.i1n.8393

Hou, J., Gao, X., & Entz, M. (2025). Enhancing zinc and iron bioavailability through crop rotation and organic farming: Insights from a long-term study. *Field Crops Research*. https://doi.org/10.1016/j.fcr.2024.109710

Huertas, R., Karpinska, B., Ngala, S., Mkandawire, B., Maling'a, J., Wajenkeche, E., Kimani, P. M., Boesch, C., Stewart, D., Hancock, R. D., & Foyer, C. H. (2023). Biofortification of common bean (*Phaseolus vulgaris* L.) with iron and zinc: Achievements and challenges. *Food and Energy Security, 12*(2), e406. https://doi.org/10.1002/fes3.406

Hui, X., Luo, L., Chen, Y., Palta, J., & Wang, Z. (2025). Zinc agronomic biofortification in wheat and its drivers: A global meta-analysis. *Nature Communications, 16*. https://doi.org/10.1038/s41467-025-58397-y

Hussain, A., Jiang, W., Wang, X., Shahid, S., Saba, N., Ahmad, M., Dar, A., Masood, S., Imran, M., & Mustafa, A. (2022). Mechanistic impact of zinc deficiency in human development. *Frontiers in Nutrition, 9*. https://doi.org/10.3389/fnut.2022.717064

Ishfaq, M., Wakeel, A., Shahzad, M., Kiran, A., & Li, X. (2021). Severity of zinc and iron malnutrition linked to low intake through a staple crop: A case study in east-central Pakistan. *Environmental Geochemistry and Health, 43*, 4219–4233. https://doi.org/10.1007/s10653-021-00912-3

Jalal, A., Júnior, E., & Filho, M. (2024). Interaction of zinc mineral nutrition and plant growth-promoting bacteria in tropical agricultural systems: A review. *Plants, 13*. https://doi.org/10.3390/plants13050571

Jamali, I., & , Z. (2025). Zinc-induced plant resilience against abiotic stresses: Physiological, biochemical and molecular insights – A review. *Pakistan Journal of Agriculture*. https://doi.org/10.38211/pja.2025.02.120

Jan, A., Hadi, F., Ditta, A., Suleman, M., & Ullah, M. (2022). Zinc-induced anti-oxidative defense and osmotic adjustments to enhance drought stress tolerance in sunflower (*Helianthus annuus* L.). *Environmental and Experimental Botany*. https://doi.org/10.1016/j.envexpbot.2021.104682

Kathula, K., Manohar, K., Sagar, L., & Gaikwad, D. (2023). Effect of different zinc fertilization methods on growth and productivity of summer maize (*Zea mays* L.). *Agricultural Science Digest - A Research Journal*. https://doi.org/10.18805/ag.d-5732

Kaur, H., & Garg, N. (2021). Zinc toxicity in plants: A review. *Planta, 253*. https://doi.org/10.1007/s00425-021-03642-z

Khan, M., Aleinikovienė, J., & Butkevičienė, L. (2024). Innovative organic fertilizers and cover crops: Perspectives for sustainable agriculture in the era of climate change and organic agriculture. *Agronomy*. https://doi.org/10.3390/agronomy14122871

Khan, S. T., Malik, A., Alwarthan, A., & Shaik, M. R. H. (2022). The enormity of the zinc deficiency problem and available solutions: An overview. *Arabian Journal of Chemistry, 15*(3), 103668. https://doi.org/10.1016/j.arabjc.2021.103668

Khokhar, J., Broadley, M., & Ander, E. (2024). Soil zinc surveillance frameworks can inform human nutrition studies: Opportunities in India. *Frontiers in Soil Science*. https://doi.org/10.3389/fsoil.2024.1421652

Kiani, B., Arshad, I., Nazir, S., Saleh, I., Kiani, S., Zomot, N., Al-Qahtani, W., Alfuraydi, A., & Abdel-Maksoud, M. (2024). Innovative approaches for sustainable zinc nutrition and crop yield enhancement in pea plants using zinc oxide nanoparticles. *Journal of Soil Science and Plant Nutrition, 24*, 5829–5840. https://doi.org/10.1007/s42729-024-01944-1

Kumar, A., Singh, K., Verma, P., Singh, O., Panwar, A., Singh, T., Kumar, Y., & Raliya, R. (2022). Effect of nitrogen and zinc nanofertilizer with the organic farming practices on cereal and oil seed crops. *Scientific Reports, 12*. https://doi.org/10.1038/s41598-022-10843-3

Kumar, D., Patel, K., Ramani, V., Shukla, A., Behera, S., & Patel, R. (2022). Influence of different rates and frequencies of Zn application to maize–wheat cropping on crop productivity and Zn use efficiency. *Sustainability*. https://doi.org/10.3390/su142215091

Kumar, S., Kumar, S., & Mohapatra, T. (2021). Interaction between macro- and micro-nutrients in plants. *Frontiers in Plant Science, 12*. https://doi.org/10.3389/fpls.2021.665583

Liu, H., Gan, W., Rengel, Z., & Zhao, P. (2016). Effects of zinc fertilizer rate and application method on photosynthetic characteristics and grain yield of summer maize. *Journal of Soil Science and Plant Nutrition, 16*, 550–562. https://doi.org/10.4067/s0718-95162016005000045

Liu, J., Wu, H., & Riaz, I. (2025). Advanced technologies for smart fertilizer management in agriculture: A review. *IEEE Access, 13*, 139766–139790. https://doi.org/10.1109/access.2025.3594361

Lowe, N., Hall, A., Broadley, M., Foley, J., Boy, E., & Bhutta, Z. (2024). Preventing and controlling zinc deficiency across the life course: A call to action. *Advances in Nutrition, 15*. https://doi.org/10.1016/j.advnut.2024.100181

Majumdar, A., Saraf, S., Sahu, C., Pathak, P., & Baghel, M. (2025). Zinc deficiency: Impact on growth, immunity, and the role of plant-based nutritional strategies. *Chemistry & Biodiversity, 22*. https://doi.org/10.1002/cbdv.202500325

Manzeke-Kangara, M., Joy, E., Mtambanengwe, F., Chopera, P., Watts, M., Broadley, M., & Mapfumo, P. (2021). Good soil management can reduce dietary zinc deficiency in Zimbabwe. *CABI Agriculture and Bioscience, 2*. https://doi.org/10.1186/s43170-021-00057-4

Mapodzeke, J., Adil, M., Sehar, S., Karim, M., Saddique, M., Ouyang, Y., & Shamsi, I. (2021). Myriad of physio-genetic factors determining the fate of plant under zinc nutrient management. *Environmental and Experimental Botany, 189*, 104559. https://doi.org/10.1016/j.envexpbot.2021.104559

Mattiello, E., Ruiz, H., Neves, J., Ventrella, M., & Araújo, W. (2015). Zinc deficiency affects physiological and anatomical characteristics in maize leaves. *Journal of Plant Physiology, 183*, 138–143. https://doi.org/10.1016/j.jplph.2015.05.014

Matumba, A., Nalivata, P., Bailey, E., Lark, M., Broadley, M., Ander, L., & Chimungu, J. (2025). Biofortification of common bean: Critical analysis of genetic and agronomic strategies as viable alternatives to tackling zinc deficiency in developing countries. *Sustainability*. https://doi.org/10.3390/su17188510

Meena, S., Sharma, S., Singh, P., Ram, A., Meena, B., Jain, D., Singh, D., Debnath, S., Yadav, S., Dhakad, U., Verma, P., Meena, J., & Nandan, S. (2023). Tillage-based nutrient management practices for sustaining productivity and soil health in the soybean-wheat cropping system in Vertisols of the Indian semi-arid tropics. *Frontiers in Sustainable Food Systems*. https://doi.org/10.3389/fsufs.2023.1234344

Monib, A., Niazi, P., & Sediqi, S. (2023). Investigating approaches for optimizing agricultural yield: A comprehensive review of the crucial role of micronutrients in enhancing plant growth and maximizing production. *Journal for Research in Applied Sciences and Biotechnology*. https://doi.org/10.55544/jrasb.2.5.26

Muhammad, F., Haq, M., Khan, M., Shafique, M., Bashir, S., Alizai, S., Khan, M., M., Irum, A., & Raza, M. (2022). Unlocking the potential of zinc (Zn) efficiency for enhanced crop production in low-Zn environments. *Indus Journal of Agriculture and Biology*. https://doi.org/10.59075/ijab.v1i1.143

N, G., S, R., D, K., & R, R. (2019). Zinc status in the soils of Karnataka and response of horticultural crops to zinc application: A meta-analysis. *Journal of Horticultural Sciences*. https://doi.org/10.24154/jhs.2019.v14i02.003

Nadeem, F., Abbas, S., Waseem, F., Ali, N., Mahmood, R., Bibi, S., Deng, L., Wang, R., Zhong, Y., & Li, X. (2024). Phosphorus (P) and zinc (Zn) nutrition constraints: A perspective of linking soil application with plant regulations. *Environmental and Experimental Botany*. https://doi.org/10.1016/j.envexpbot.2024.105875

Nandal, V., & Solanki, M. (2021). The Zn as a vital micronutrient in plants. *Journal of Microbiology, Biotechnology and Food Sciences*. https://doi.org/10.15414/jmbfs.4026

Natasha, N., Shahid, M., Bibi, I., Iqbal, J., Khalid, S., Murtaza, B., Bakhat, H. F., Farooq, A. B. U., Amjad, M., Hammad, H. M., Niazi, N. K., & Arshad, M. (2022). Zinc in soil-plant-human system: A data-analysis review. *The Science of the Total Environment, 808*, 152024. https://doi.org/10.1016/j.scitotenv.2021.152024

Noulas, C., Tziouvalekas, M., & Karyotis, T. (2018). Zinc in soils, water and food crops. *Journal of Trace Elements in Medicine and Biology: Organ of the Society for Minerals and Trace Elements, 49*, 252–260. https://doi.org/10.1016/j.jtemb.2018.02.009

Omer, E., Szlatenyi, D., Csenki, S., Alrwashdeh, J., Czakó, I., & Láng, V. (2024). Farming practice variability and its implications for soil health in agriculture: A review. *Agriculture*. https://doi.org/10.3390/agriculture14122114

Panchal, A., & Maitreya, B. (2023). A review on exploring the significance of micronutrients in crop production. *International Association of Biologicals and Computational Digest*. https://doi.org/10.56588/iabcd.v2i2.183

Pandya, P., Kumar, S., Sakure, A., Rafliya, R., & Patil, G. (2023). Zinc oxide nanopriming elevates wheat drought tolerance by inducing stress-responsive genes and physio-biochemical changes. *Current Plant Biology*. https://doi.org/10.1016/j.cpb.2023.100292

Pankaj, P., & Nirala, Y. (2024). Effect of zinc on qualitative and quantitative traits of major vegetable crops. *International Journal of Advanced Biochemistry Research*. https://doi.org/10.33545/26174693.2024.v8.i10sl.2617

Paramesh, V., Dhar, S., Dass, A., Kumar, B., Kumar, A., El-Ansary, D., & Elansary, H. (2020). Role of integrated nutrient management and agronomic fortification of zinc on yield, nutrient uptake and quality of wheat. *Sustainability, 12*, 3513. https://doi.org/10.3390/su12093513

Polwaththa, K. P. G. D. M., Amarasinghe, A. A. Y., & Nandasena, G. P. M. S. (2024). A review of innovative fertilization strategies in precision agriculture. *Open Access Research Journal of Science and Technology, 12*(2), 49–57. https://doi.org/10.53022/oarjst.2024.12.2.0137

Poudel, P., Connolly, E., Kwasniewski, M., Lambert, J., & Di Gioia, F. (2024). Zinc biofortification via fertigation using alternative zinc sources and concentration levels in pea, radish, and sunflower microgreens. *Scientia Horticulturae*. https://doi.org/10.1016/j.scienta.2024.113098

Pradhan, A., Beura, K., Das, R., Ingle, S., Mandal, B., Hazra, G., De, N., Polara, K., Kachroo, D., Sharma, A., & Patel, K. (2025). Zinc in the soil–plant continuum: A long-term perspective from selected Inceptisols in India. *Soil Use and Management, 41*. https://doi.org/10.1111/sum.70056

Praharaj, S., Skalický, M., Maitra, S., Bhadra, P., Shankar, T., Brestič, M., Hejnak, V., Vachová, P., & Hossain, A. (2021). Zinc biofortification in food crops could alleviate the zinc malnutrition in human health. *Molecules, 26*. https://doi.org/10.3390/molecules26123509

Priya, E., Sarkar, S., & Maji, P. (2024). A review on slow-release fertilizer: Nutrient release mechanism and agricultural sustainability. *Journal of Environmental Chemical Engineering*. https://doi.org/10.1016/j.jece.2024.113211

Rahman, K., Juraimi, A., Karim, S., Hatta, A., Sulaiman, Z., Khan, M., Alam, M., Ahmed, I., Mokarroma, N., Ahmed, S., Rahman, M., & Hossain, A. (2024). Improving the productivity and nutritional values of sweet potato (*Ipomoea batatas* L.) with a combination of soil and foliar zinc. *Current Applied Science and Technology*. https://doi.org/10.55003/cast.2023.257789

Rajendiran, S., Raghupathi, H., Ramachandran, S., Raghu, B., & Venugopalan, R. (2024). Effect of zinc fertilization on productivity and zinc uptake in chilli-finger millet-amaranthus system. *Journal of Applied Horticulture*. https://doi.org/10.37855/jah.2024.v26i03.60

Rana, L., Kumar, N., Rajput, J., Sow, S., Ranjan, S., Kumari, S., Pradhan, J., Kumar, A., Singh, S., Kumar, A., Jha, C., Kumari, M., Singh, D., & Sahoo, R. (2024). Unlocking potential: The role of zinc fortification combating hidden hunger and enhancing nutritional security. *Journal of Experimental Agriculture International*. https://doi.org/10.9734/jeai/2024/v46i102986

Ravishankar, L., Puranik, N., Lekkala, V., Lomada, D., Reddy, M., & Maurya, A. (2025). ZnO nanoparticles: Advancing agricultural sustainability. *Plants, 14*. https://doi.org/10.3390/plants14152430

Raza, M. B., Meena, B. P., Behera, S. K., Rani, K., Wanjari, R. H., Biswas, A. K., Islam, S., Dash, A. K., & Datta, S. P. (2025). Long-term influence of addition of organic and inorganic sources of nutrients on soil Zn fractions, yield and Zn uptake by maize (*Zea mays* L.). *Journal of Soil Science and Plant Nutrition, 25*, 809–827. https://doi.org/10.1007/s42729-024-02168-z

Regar, K., Kumar, V., Chandola, J., Patel, S., Singh, A., Kundu, M., & Singh, S. (2022). Zinc fertilization: Effects on nutrients availability and productivity of rice (*Oryza sativa* L.). *International Journal of Plant & Soil Science*. https://doi.org/10.9734/ijpss/2022/v34i1230958

Saleem, H., Usman, K., Rizwan, M., Jabri, H., & Alsafran, M. (2022). Functions and strategies for enhancing zinc availability in plants for sustainable agriculture. *Frontiers in Plant Science, 13*. https://doi.org/10.3389/fpls.2022.1033092

Sangeetha, V., Dutta, S., Moses, J., & Anandharamakrishnan, C. (2022). Zinc nutrition and human health: Overview and implications. *eFood*. https://doi.org/10.1002/efd2.17

Sharma, A., Patni, B., Shankhdhar, D., & Shankhdhar, S. C. (2013). Zinc – An indispensable micronutrient. *Physiology and Molecular Biology of Plants, 19*(1), 11–20. https://doi.org/10.1007/s12298-012-0139-1

Shoukat, A., Maryam, U., Pitann, B., Zafar, M., Nawaz, A., Hassan, W., Seleiman, M., Saqib, Z., & Mühling, K. (2025). Efficacy of nano and conventional zinc and silicon fertilizers for nutrient use efficiency and yield benefits in maize under saline field conditions. *Plants, 14*. https://doi.org/10.3390/plants14050673

Silva, A., Borges, L., Lucini, F., Silva, G., & Santos, E. (2025). Technologies in agronomic biofortification with zinc in Brazil: A review. *Plants, 14*. https://doi.org/10.3390/plants14121828

Smaoui, A., Mahmoudi, H., Medimagh, S., Taheri, A., Zribi, F., Ouerghi, Z., & Salah, B. (2023). Physiological and biochemical responses of *Carthamus tinctorius* L. to zinc at vegetative stage. *Journal of Plant Nutrition and Soil Science*. https://doi.org/10.1002/jpln.202200339

Sreethu, S., Kaur, G., Chhabra, V., Gupta, R., Agarwal, B., & Mattar, M. (2024). Integrated nutrient management and agronomic zinc biofortification to improve wheat crop and soil health. *Journal of Plant Nutrition, 47*, 3889–3905. https://doi.org/10.1080/01904167.2024.2387812

Stangoulis, J., & Knez, M. (2022). Biofortification of major crop plants with iron and zinc - achievements and future directions. *Plant and Soil, 474*, 57–76. https://doi.org/10.1007/s11104-022-05330-7

Stuckey, J., Verdejo, J., García, S., Pinochet, D., Yáñez, C., Krutyakov, Y., & Neaman, A. (2022). Evaluating zinc nutrition in perennial ryegrass grown in an Andisol. *Geography, Environment, Sustainability*. https://doi.org/10.24057/2071-9388-2022-041

Taşpinar, K., Aytop, H., Ateş, Ö., Varol, M., Yalçin, G., Kızılaslan, F., Çakilli, H., & Toprak, S. (2025). Zinc bioavailability in semiarid agricultural regions: A soil property-based assessment. *Environmental Geochemistry and Health, 47*. https://doi.org/10.1007/s10653-025-02544-3

Tayyiba, L., Zafar, H., Gondal, A. H., Farooq, Q., Mukhtar, M. M., Hussain, R., Aslam, N., Muzaffar, A., & Sattar, I. (2021). Efficiency of zinc in plants, its deficiency and sensitivity for different crops. *Current Research in Agricultural Sciences, 8*(2), 128–134. https://doi.org/10.18488/journal.68.2021.82.128.134

Tondey, M., Kalia, A., Singh, A., Dheri, G., Taggar, M., Nepovimova, E., Krejcar, O., & Kuča, K. (2021). Seed priming and coating by nano-scale zinc oxide particles improved vegetative growth, yield and quality of fodder maize (*Zea mays*). *Agronomy, 11*, 729. https://doi.org/10.3390/agronomy11040729

Țopa, D., Căpșună, S., Calistru, A., & Ailincăi, C. (2025). Sustainable practices for enhancing soil health and crop quality in modern agriculture: A review. *Agriculture*. https://doi.org/10.3390/agriculture15090998

Tsang, B., Holsted, E., McDonald, C., Brown, K., Black, R., Mbuya, M., Grant, F., Rowe, L., & Manger, M. (2021). Effects of foods fortified with zinc, alone or cofortified with multiple micronutrients, on health and functional outcomes: A systematic review and meta-analysis. *Advances in Nutrition, 12*, 1821–1837. https://doi.org/10.1093/advances/nmab065

Xie, X., Hu, W., Fan, X., Chen, H., & Tang, M. (2019). Interactions between phosphorus, zinc, and iron homeostasis in nonmycorrhizal and mycorrhizal plants. *Frontiers in Plant Science, 10*. https://doi.org/10.3389/fpls.2019.01172

Yadav, A., Tulluru, N., Panda, M., Singh, A., Nagar, B., H., & Rajbhar, R. (2023). Impact of boron and zinc on vegetables: A review. *International Journal of Environment and Climate Change*. https://doi.org/10.9734/ijecc/2023/v13i103060

Younas, N., Fatima, I., Ahmad, I., & Ayyaz, M. (2022). Alleviation of zinc deficiency in plants and humans through an effective technique; biofortification: A detailed review. *Acta Ecologica Sinica*. https://doi.org/10.1016/j.chnaes.2022.07.008

Zeb, T., Rehman, J., & Ali, M. (2022). Effect of mode of zinc application on yield and yield components of maize. *Journal of Agriculture Sustainability and Environment*. https://doi.org/10.56556/jase.v1i2.884

Zewide, I., & Sherefu, A. (2021). Review paper on effect of micronutrients for crop production. *Nutrition and Food Processing*. https://doi.org/10.31579/2637-8914/063



*Peer-review history:*
*The peer review history for this paper can be accessed here:*
*https://pr.sdiarticle5.com/review-history/157486*