Review Article

The Critical Role of Zinc in Improving Public Health and Crop Quality: Examining Challenges and Strategies for Soil Enrichment in Developing Countries

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Abstract

Zinc (Zn) deficiency poses a significant public health challenge, particularly in vulnerable communities with limited access to Zn-rich foods. This review article critically examines the role of biofortification as a sustainable strategy to enhance Zn levels in agricultural products, thereby improving nutritional quality and addressing health disparities. We employed a comprehensive literature review, sourcing data from reputable scientific databases such as ScienceDirect, Google Scholar, and Scopus, focusing on empirical studies that highlight effective biofortification methods. The findings reveal that integrating soil amendments, such as microbial inoculants and organic fertilizers, significantly enhances Zn availability, and uptake in crops. In addition, we explore the impact of crop rotation and intercropping systems on soil health and nutrient cycling, emphasizing the importance of diverse planting strategies. This article aims to provide actionable insights for researchers and practitioners in the field of soil fertility, advocating for innovative approaches to combat Zn deficiency through enhanced agricultural practices. By synthesizing current research, we offer new strategies for optimizing Zn use in sustainable agriculture, ultimately contributing to improved health outcomes and food security in affected communities. This review underscores the urgent need for targeted interventions and public awareness initiatives to promote Zn-rich diets, thereby fostering resilience against nutritional deficiencies and enhancing overall community well-being.

Keywords: Biofortification, nutritional status, public health, zinc

INTRODUCTION

Zinc (Zn) deficiency is a major global health issue, affecting immune function, growth, and overall health, particularly in developing countries where diets are low in Zn. This deficiency increases susceptibility to infections and diseases, especially in vulnerable populations with limited access to Zn-rich foods. Urgent interventions are needed to address this nutritional shortfall and improve health outcomes.[1] Zn is crucial for immune function, especially in T cell production. A deficiency weakens immune responses, increasing vulnerability to infections such as influenza and pneumonia. This public health issue impacts individual and community well-being. Raising awareness of Zn's importance and improving access to Zn-rich foods are essential steps to combat this deficiency.[2,3]

Zn deficiency significantly reduces the nutritional value of agricultural products, particularly affecting crops that do not naturally contain adequate Zn. This inadequacy hampers the ability of these crops to meet community nutritional needs, especially in diets that are low in diversity and heavily reliant on grains and starchy foods.[4] Consequently, this situation increases the risk of malnutrition and related health issues, highlighting the urgent need for interventions to enhance Zn levels in staple crops and improve dietary quality.[5] The decline in Zn concentration in agricultural products reduces their nutritional value, especially in grains and legumes, affecting community health. This deficiency leads to inadequate nutrients for growth and increases reliance on

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supplements, burdening families and healthcare systems while worsening economic and social challenges.[6]

Improving the nutritional quality of agricultural is essential [Figure 1].[7] Techniques such as fertilizing with Zn-containing materials and enhancing crop diversity can effectively raise Zn levels, thereby improving the nutritional value, production, and quality of these products. In addition, promoting the consumption of Zn-rich foods and educating communities about the importance of diverse nutrition can enhance nutritional status and public health.[8] These initiatives are integral to comprehensive public health and sustainable agriculture strategies, ultimately improving the quality of life for individuals and communities.[9]

Addressing Zn deficiency and its effects on the nutritional value of agricultural products is crucial for sustainable development initiatives focused on enhancing community nutrition.[10] By implementing targeted programs and strategies, we can work toward a healthier, more sustainable future where everyone has access to adequate and nutritious food, ultimately improving health and quality of life.[11] The main objective of this review article is to examine the necessary strategies for the biofortification of agricultural products with Zn.

METHODS

Literature search strategy

The literature search strategy ensures that the review is built on a robust and comprehensive foundation of existing knowledge. A systematic approach was employed to identify relevant studies published over the last decade (2015–2025) in high-impact journals. The databases consulted included Web of Science, Scopus, PubMed, and Google Scholar. These platforms were chosen for their extensive coverage of peer-reviewed research in environmental science, plant science, agronomy, and nutrition. The search focused on keywords such as "zinc biofortification," "Zn uptake mechanisms," "agronomic biofortification," "genetic biofortification," "Zn nanoparticles," "biochar in Zn biofortification," and "Zn deficiency." Boolean operators (AND, OR) were used to refine searches. For example, combinations such as "zinc biofortification AND agronomic approaches" or "Zn deficiency OR malnutrition AND crops" ensured a comprehensive retrieval of studies addressing various facets of zinc biofortification.

In addition, backward citation tracking was conducted to identify seminal papers cited in recent high-impact articles. Forward citation tracking was also used to locate newer studies citing foundational works. This iterative process allowed the inclusion of both foundational research and cutting-edge advancements.

Inclusion and exclusion criteria

To maintain the relevance and quality of the review, strict inclusion and exclusion criteria were applied during the selection process. Studies were included if they met the following criteria:

- Publication Date: Only studies published between 2015 and 2025 were considered to ensure that the review reflects current advancements
- Relevance: Articles focusing on Zn biofortification in plants through agronomic, genetic, or biotechnological approaches were prioritized
- Study Type: Peer-reviewed original research articles, meta-analyses, systematic reviews, and high-quality conference proceedings were included in the study.

Data extraction and analysis

After identifying relevant studies through the literature search strategy and applying inclusion/exclusion criteria, data extraction was conducted systematically. Key information was extracted from each study using a standardized data extraction form that included:

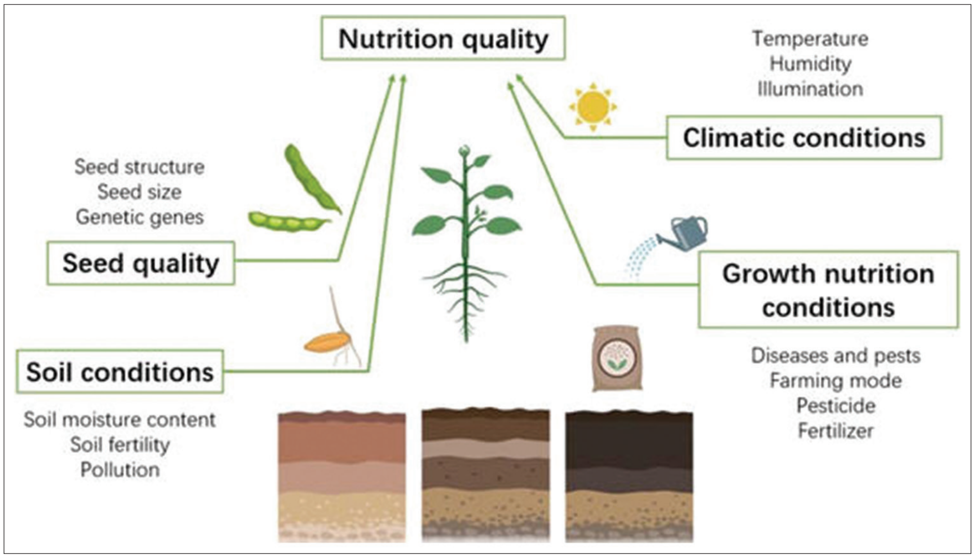

Figure 1: The factors influencing the nutritional quality of crops[7]

- Study Details: Author(s), year of publication, journal name, and study location
- Research Focus: Agronomic practices (e.g., soil or foliar application)
- Methodologies Used: Experimental designs (e.g., field trials vs. greenhouse studies), statistical analyses performed, and technologies employed (e.g., CRISPR-Cas9).

The extracted data were then analyzed qualitatively and quantitatively:

- Qualitative Analysis: Thematic synthesis was used to identify recurring trends across studies (e.g., effectiveness of foliar application vs. soil application)
- Quantitative Analysis: Meta-analysis techniques were applied where possible to calculate pooled effect sizes for interventions such as Zn fertilization or genetic modifications.

RESULTS AND DISCUSSION

Agronomic practices

Agronomic techniques for mitigating Zn deficiency are crucial for improving crop yield and nutritional quality, especially in Zn-deficient soils. Key strategies include the application of Zn fertilizers, such as Zn sulfate ($ZnSO_4$), which enhances soil bioavailability, and foliar sprays that provide a quick remedy for deficiencies. Seed treatments with Zn-coated seeds can also help protect young plants. Long-term approaches involve crop rotation with Zn-efficient species, maintaining optimal soil pH, and increasing organic matter to improve nutrient retention [Figure 2].[12] By integrating these practices, farmers can effectively address Zn deficiency while promoting sustainable agricultural systems and enhancing soil health.

Soil amendments

Zn fertilizers play a critical role in improving crop yield and quality, especially in Zn-deficient soils. They enhance nutrition, photosynthesis, and resilience to diseases and environmental stresses. Foliar sprays enable faster uptake compared to soil applications, while soil testing and understanding crop-specific Zn needs to ensure precise, effective fertilization strategies tailored to local conditions.[13] Recent studies have demonstrated that applying $ZnSO_4$ at rates of 25–50 kg/ha can boost Zn uptake by up to 40%, particularly in cereals such as barley and rice.[14] In addition, long-term field experiments have revealed that repeated soil applications can sustain high Zn levels in grains over multiple growing seasons, making it a reliable strategy for regions with chronic Zn-deficient soils.[15]

Table 1[16] aims to clarify how varying application rates of Zn and Fe influence their respective concentrations in maize grains. This information can significantly aid biofortification strategies designed to combat micronutrient deficiencies in human diets.[16] With many individuals' worldwide facing shortages of these essential nutrients, the significance of this research becomes even more pronounced. Ultimately, the findings from this study could provide effective solutions for farmers and nutrition experts, enabling them to utilize scientific and practical methods to improve the quality of food products and contribute to better public health outcomes.[16]

The type, timing, and method of Zn fertilizer application are crucial for crop uptake efficiency. Zn sources such as Zn oxide and $ZnSO_4$ differ in solubility and soil availability, influencing their effectiveness under varying agricultural conditions. Combining Zn fertilizers with organic amendments improves bioavailability by enhancing soil structure and microbial activity, boosting nutrient absorption. This strategy addresses Zn deficiency while promoting soil health, fostering sustainable farming practices that strengthen crop resilience and yield.[17]

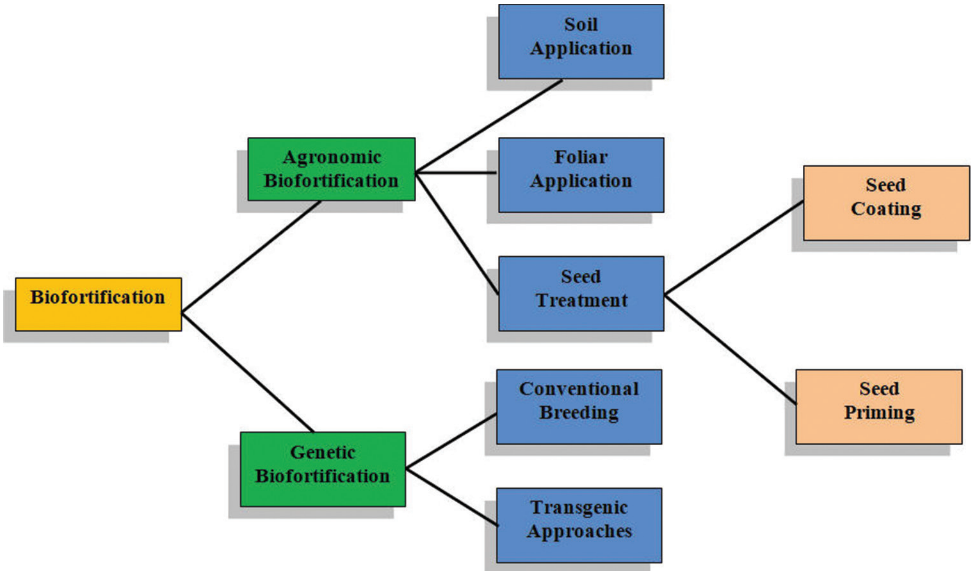

Figure 2: Agronomic techniques for mitigating zinc deficiency[12]

Investigating microbial community role in enhancing Zn availability is a promising strategy for optimizing crop nutrient uptake.[18,19] Research shows that soil microorganisms, such as *Bacillus* spp. and *Rhizobium*, enhance Zn bioavailability by solubilizing it from inorganic sources and promoting root exudation. These microbes improve Zn fertilizer efficiency, soil structure, and health, supporting sustainable agriculture. Combining biological methods with traditional fertilization, crop rotation, and intercropping systems further boosts nutrient uptake. For instance, legumes like white clover enhance nitrogen fixation and microbial activity, increasing heavy metal solubility. Diverse planting strategies optimize root exudates, critical for mobilizing Zn and fostering plant growth and resilience against environmental stress.[20]

Soil and plant factors are key to Zn uptake and accumulation, and vital for plant health and productivity. Soil pH, organic matter, and competing ions control Zn bioavailability; high pH reduces Zn solubility, whereas organic matter's effect depends on its composition. Extensive root systems improve Zn access, with studies linking optimized root growth to enhanced Zn uptake, especially when fertilizers are properly applied. Nutrient interactions, like excessive phosphorus inhibiting Zn absorption, further influence availability. Understanding these dynamics is crucial for creating fertilization strategies that maximize Zn efficiency and support healthy crop yields across diverse soils [Figure 3].[21]

Foliar application

Zn solutions are essential for improving plant health and crop yields by enhancing nutrient absorption and metabolic functions. They boost chlorophyll production and enzyme activity, which support photosynthesis and energy transfer, leading to stronger growth and increased disease resistance.[19] In addition, Zn helps crops withstand environmental stressors

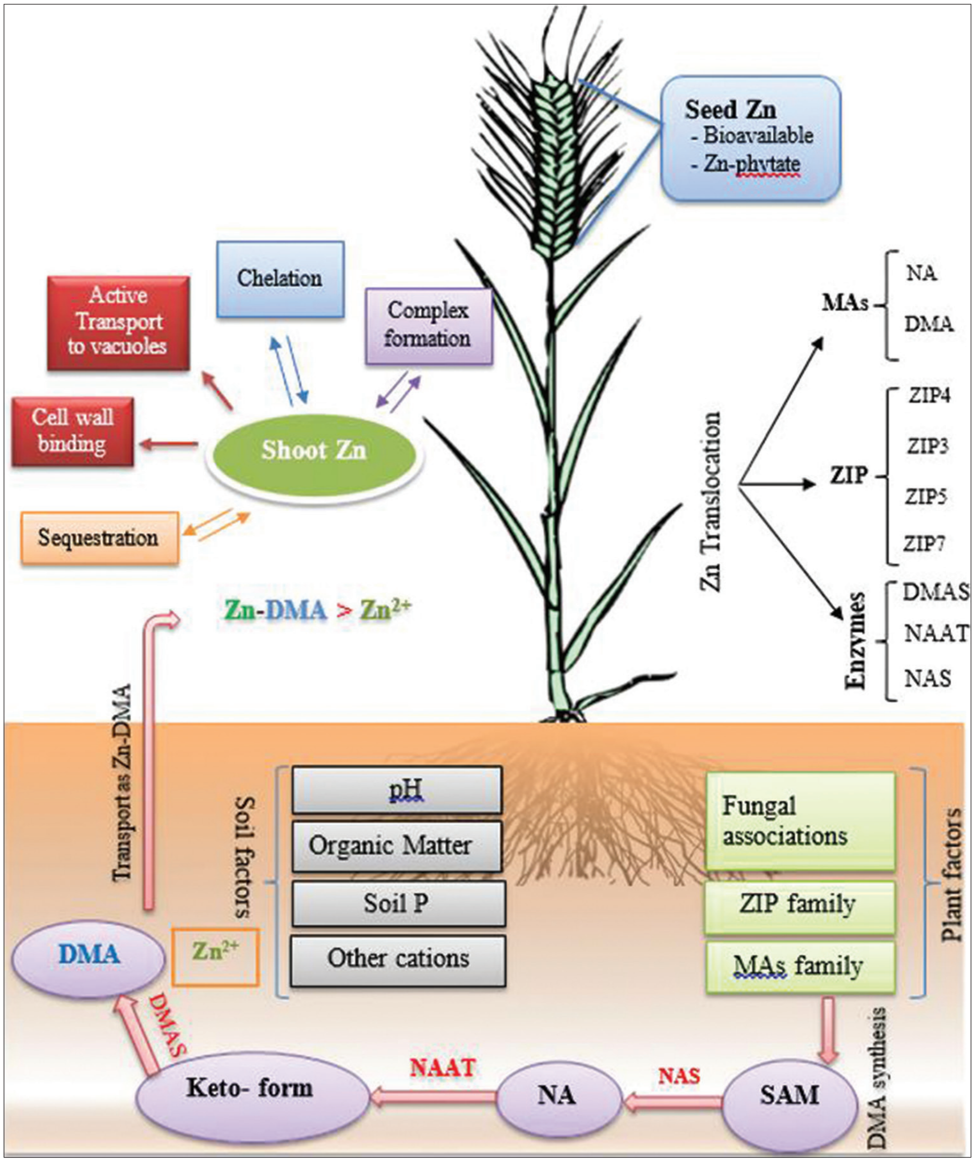

Figure 3: Soil and plant factors affect zinc uptake and accumulation[21]

like drought and high temperatures, promoting root development for better access to water and nutrients. Studies have shown that foliar sprays of 0.5% $ZnSO_4$ can increase grain Zn concentration by 15%–25% within a single growing season.[22]

As a result, Zn solutions are crucial for farmers seeking to optimize agricultural practices and ensure sustainable food production in the face of climate change.[20] Strategic Zn use is crucial for mitigating heavy metal contamination in agricultural soils, protecting plant health and food safety. Zn limits toxic metal uptake and translocation in plants while enhancing membrane stability and antioxidant activity to bolster stress resilience. Beyond its role as a nutrient, Zn is vital for sustaining agricultural productivity and food security amid environmental challenges.[23]

Integrating Zn solutions into crop management enhances resilience against pests by activating defense genes and reducing disease severity. Zn promotes soil health through increased microbial activity and nutrient cycling while also mitigating heavy metal toxicity. This approach boosts yields and improves nutritional quality, addressing food security linked to Zn deficiency. With many soils lacking bioavailable Zn, its application is crucial for restoring nutrient balance and supporting sustainable agriculture.[24]

Crop rotation

The strategic implementation of crop rotation is pivotal in enhancing carbon sequestration, thereby addressing climate change.[25] By integrating legume crops that fix atmospheric nitrogen, farmers can improve soil fertility and decrease reliance on synthetic fertilizers, which contribute to greenhouse gas emissions [Figure 4]. The practice of fallowing allows land to recuperate, enriching soil health through increased organic matter and microbial diversity while disrupting pest cycles.[25] This approach shows how crop rotation enhances ecological balance and food security. Cover crops prevent soil erosion and suppress weeds, supporting sustainable agriculture. Crop rotations improve water management for drought resilience, while agroforestry boosts biodiversity and organic matter. Integrating pest management reduces chemical pesticide use, promoting ecosystem stability and safeguarding yields.[26]

Legumes such as chickpeas and lentils enhance soil Zn availability for subsequent crops through nitrogen fixation and improved soil structure.[27] Crops such as wheat and barley enhance Zn levels by utilizing organic matter and stimulating beneficial microbes, enriching soil nutrients, and reducing reliance on chemical fertilizers. Cover crops such as clover and vetch further increase Zn by adding organic matter and fostering microbial diversity, aiding nutrient cycling. This integrated strategy boosts yields, promotes biodiversity, and ensures long-term ecosystem health and productivity.[28]

The integration of Zn-solubilizing microbes (ZSM) into agricultural practices offers a sustainable approach to enhance

Table 1: Influence of Zn and Fe application on the Zn and Fe concentrations in maize grains[16]

Treatments	Fe content (mg kg^{-1})	Percentage increase	Zn content (mg kg^{-1})	Percentage increase
NPK	74.1	-	14.3	-
NPK +10 kg Zn and Fe	91.6	23.6	18.3	28.0
NPK +20 kg Zn and Fe	107.6	45.2	23.2	62.2
NPK +30 kg Zn and Fe	122.7	65.6	25.1	75.5
NPK +0.1 % foliar spray of Zn and Fe	153.6	107.3	31.8	122.4

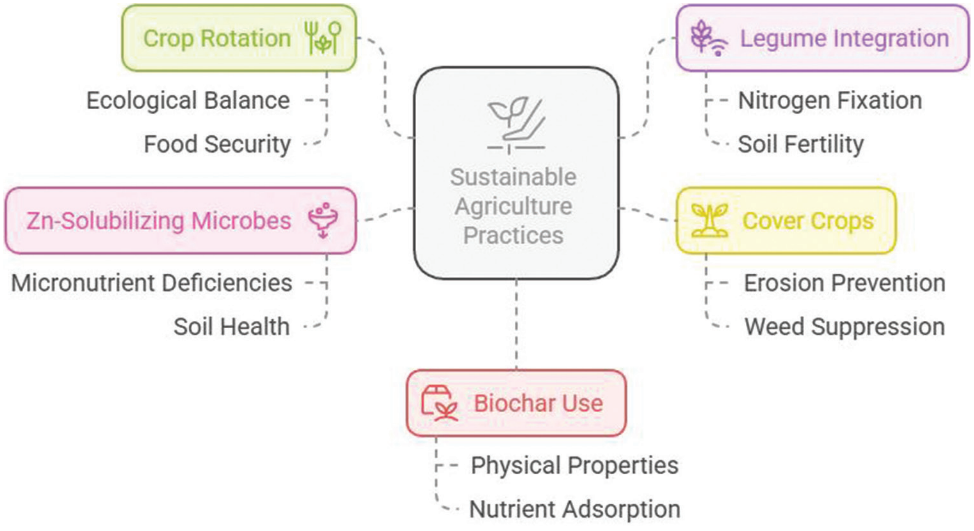

Figure 4: Sustainable agriculture practices and soil health

Zn availability in soils, thereby addressing micronutrient deficiencies in crops and human health. These beneficial microorganisms not only solubilize Zn from insoluble forms but also improve soil health by promoting nutrient uptake and plant resilience against stressors.[29] By leveraging ZSM, farmers can reduce reliance on synthetic fertilizers while fostering ecological balance through practices such as intercropping and conservation tillage, which optimize land use and preserve microbial habitats. Furthermore, incorporating biochar into soil enhances physical properties and nutrient adsorption, further increasing Zn solubility.[30] Agroforestry enriches soil nutrients and supports beneficial microbes. Policy support and education are vital for promoting these practices, offering knowledge sharing and financial incentives. These strategies enhance food security and foster environmental stewardship for resilient agricultural landscapes.[31] Field trials have shown that biochar-amended soils can increase grain Zn concentration by up to 30%, particularly in sandy or degraded soils.[32]

Bacterial or fungi inoculants for zinc solubilization

Beneficial microorganisms and fungi enhance Zn bioavailability by solubilizing soil-bound forms and promoting nutrient cycling. They produce organic acids and enzymes that make Zn more accessible to plants while improving soil health.[33] Beneficial microorganisms enhance Zn uptake by forming symbiotic relationships with plant roots, increasing nutrient absorption. Nonsymbiotic plant growth-promoting rhizobacteria also improve phosphorus assimilation in nutrient-poor soils.[34]

The efficacy of Zn-solubilizing bacteria in promoting plant growth and enhancing the biofortification of cereal crops represents a critical area of research within the field of agricultural microbiology and sustainable farming practices. These beneficial microorganisms play a significant role in soil health by solubilizing Zn, making it more available for plant uptake.[35] Table 2[35] delves into the various mechanisms through which these bacteria operate, including their interactions with soil components and plant roots.[35] By facilitating Zn availability in the soil, they not only improve nutrient uptake but also contribute to increased overall crop yield. This is particularly important in addressing the growing concern of micronutrient deficiencies in human diets, as cereals are staple foods for a large portion of the global population. Understanding these interactions can lead to more effective agricultural practices that enhance both crop productivity and nutritional quality.

Moreover, Fungi play a crucial role in enhancing Zn availability in the soil, as they can solubilize Zn through various biochemical processes and improve its uptake by plants.[36] In addition to their role in solubilizing Zn, fungi can also interact symbiotically with plant roots, forming mycorrhizal associations that enhance nutrient uptake beyond just Zn. These relationships not only improve the bioavailability of essential micronutrients but also contribute to overall soil health by increasing organic matter and promoting microbial diversity.[37] Interestingly, certain fungal species have been found to thrive in Zn-contaminated environments, demonstrating an ability to adapt to high metal concentrations while facilitating the detoxification process for plants.[38] This dual capacity positions fungi as vital players in both enhancing agricultural productivity and remediating contaminated soils, ultimately fostering a more sustainable ecosystem. Recent studies have shown that mycorrhizal fungi can trigger systemic resistance in host plants, enabling them to better withstand biotic and abiotic stresses such as drought or pathogen attack.[39,40] This symbiotic relationship not only bolsters plant health but also contributes to improved soil structure and fertility through increased organic matter decomposition and nutrient cycling. Furthermore, as fungi adapt to thrive in Zn-contaminated soils, they may play a pivotal role in bioremediation strategies aimed at restoring ecosystems affected by heavy metal pollution, thereby highlighting their importance in sustainable agricultural practices and ecological conservation efforts.[41]

Biotechnology approaches

Genetic engineering enhances zinc content in crops

Transgenic methods introduce specific genes into a plant's genome to enhance its nutritional profile, including Zn content, leading to increased nutrient bioavailability. In contrast, CRISPR technology provides a refined gene-editing tool, allowing scientists to target and modify DNA sequences involved in Zn uptake and storage in crops.[42] Both methods hold great promise for addressing micronutrient deficiencies in populations reliant on staple crops, ultimately contributing to improved public health and food security.[43] Recent studies have demonstrated the utility of CRISPR-Cas9 in enhancing Zn biofortification by targeting key regulatory genes such as nicotianamine synthase (*OsNAS*) and Zn transporter proteins. For instance, editing the *OsNAS2* promoter in rice has been

Table 2: Effectiveness of Zn solubilizing bacteria for enhancing plant growth and bio-fortification of cereals[35]

Name of bacterial strain	Crop	Experimental condition	Response/results
Azotobacter; *Azospirillum*	Corn	Greenhouse	Caused significant increase in Zn contents of grain
Pseudomonas; *Bacillus* spp.	Maize	Pot	Significantly enhanced total dry mass (12.96 g) and uptake of N (2.268%), K (2.0%), Mn (60 ppm), and Zn (278.8 ppm)
Endophytic strains, *Sphingomonas* spp. SaMR12; *Enterobacter* spp., SaCS20	Rice	Greenhouse	Increased Zn bioavailability in rhizosphere soils and elevated grain yields and Zn densities in grains
Providencia spp. PW5, *Anabaena* spp. CW1, *Calothrix* spp. CW2, and *Anabaena* spp. CW3	Wheat	Field	Improved the nutritional quality of wheat grains, in terms of protein content and important micronutrients (Fe, Cu, Zn, and Mn)

shown to increase Zn uptake and translocation by disrupting inhibitory cis-regulatory elements, leading to higher grain Zn concentrations and improved yield traits.[44]

One successful example of genetic modification aimed at improving Zn levels is the development of biofortified rice known as "Zn Rice," which has been engineered to increase its Zn content significantly. This innovation addresses micronutrient deficiencies in populations that rely heavily on rice as a staple food, providing an essential nutrient that supports immune function and overall health.[45]

Another notable example is "HarvestPlus," a program that has developed biofortified crops such as beans and wheat, specifically bred to enhance their Zn content, thereby contributing to better nutrition in regions, where these foods are dietary staples. These efforts not only aim to improve individual health outcomes but also seek to enhance food security and agricultural sustainability by promoting the cultivation of nutrient-rich crops in vulnerable communities. Such initiatives highlight the importance of integrating nutritional considerations into agricultural practices, ensuring that food systems can deliver not just calories but also essential vitamins and minerals necessary for a healthy population.[46]

The integration of CRISPR technology with traditional breeding methods represents a significant advancement in crop improvement, allowing researchers to develop crops with enhanced Zn content alongside traits such as drought resistance and pest tolerance, essential for adapting to climate change. This multifaceted approach aims to create resilient food systems that can support growing populations while reducing environmental impacts. As public acceptance of genetically modified organisms (GMOs) increases, bio-fortified crops may gain traction in global markets, thereby enhancing food security in various regions. In addition, CRISPR technology is being utilized to address other micronutrient deficiencies, such as iron and vitamin A, which are critical for combating malnutrition. The precision of CRISPR/Cas9 enables scientists to not only elevate nutrient levels but also improve agronomic traits like yield stability.[47]

As climate change poses ongoing challenges, the application of genome editing could yield a new class of resilient crops that thrive under adverse conditions while providing essential nutrients. This holistic approach not only addresses nutritional needs but also considers socioeconomic factors, ensuring that smallholder farmers can access these technologies. Engaging local knowledge with scientific advancements will promote sustainable practices tailored to specific contexts. Furthermore, regulatory frameworks governing CRISPR-enhanced crops will play a crucial role in their adoption and integration into farming systems, influencing public trust and acceptance as society navigates modern agricultural complexities. Ultimately, the convergence of biotechnology and policy will shape the future of agricultural strategies aimed at addressing health and environmental challenges.[43]

Challenges related to the genetic biofortification of crops encompass a range of technical, regulatory, and social factors that hinder the efficient development and adoption of biofortified varieties. Technical challenges include the limited genetic diversity available in many staple crops, which restricts the potential for conventional breeding methods to enhance micronutrient content. In cases where natural variation is insufficient, genetic engineering can provide a solution; however, this approach faces significant regulatory hurdles, as GMOs often require extensive testing and approval processes that can delay their introduction into the market. Furthermore, the cost of research and development for genetically engineered crops is high, compounded by the need to navigate complex intellectual property issues that can arise from proprietary technologies. Social acceptance also plays a critical role; farmers and consumers must be convinced of the benefits of biofortified crops, which may require effective communication strategies to address concerns over changes in crop traits such as taste or appearance. Ultimately, a successful biofortification strategy must not only overcome these challenges but also demonstrate clear agronomic advantages to ensure widespread adoption among farmers and acceptance by consumers [Figure 5].[12]

Plant breeding techniques

The integration of molecular techniques with traditional breeding methods is transforming the development of high-Zn crop varieties.[48] By employing genomic selection and marker-assisted breeding, researchers can efficiently pinpoint and select specific genes linked to Zn uptake and accumulation in plants, thus accelerating the breeding process and enhancing precision beyond conventional phenotypic evaluations. This approach not only introduces genetic diversity into breeding programs – vital for improving resilience against various stresses while preserving nutritional quality, but also aligns with the growing global demand for Zn-rich crops amid rising nutritional deficiencies.[49]

Engaging local farmers in participatory breeding programs is essential for ensuring these new cultivars are adapted to specific environmental conditions and cultural practices, fostering a sense of ownership and promoting sustainable agriculture through the integration of traditional knowledge with scientific advancements. Addressing market barriers is crucial to ensure that innovative high-Zn varieties reach those in need, emphasizing the importance of a holistic strategy that combines technical advancements with community engagement. Furthermore, successful implementation relies on a robust framework for monitoring the impact of these crops postrelease, including agronomic performance assessments and nutritional studies to confirm their effectiveness in addressing local Zn deficiencies. Collaborations among agricultural scientists, farmers, and public health experts will enhance this comprehensive approach, ultimately improving crop yield and quality while contributing significantly to community health outcomes in the context of climate change.[50]

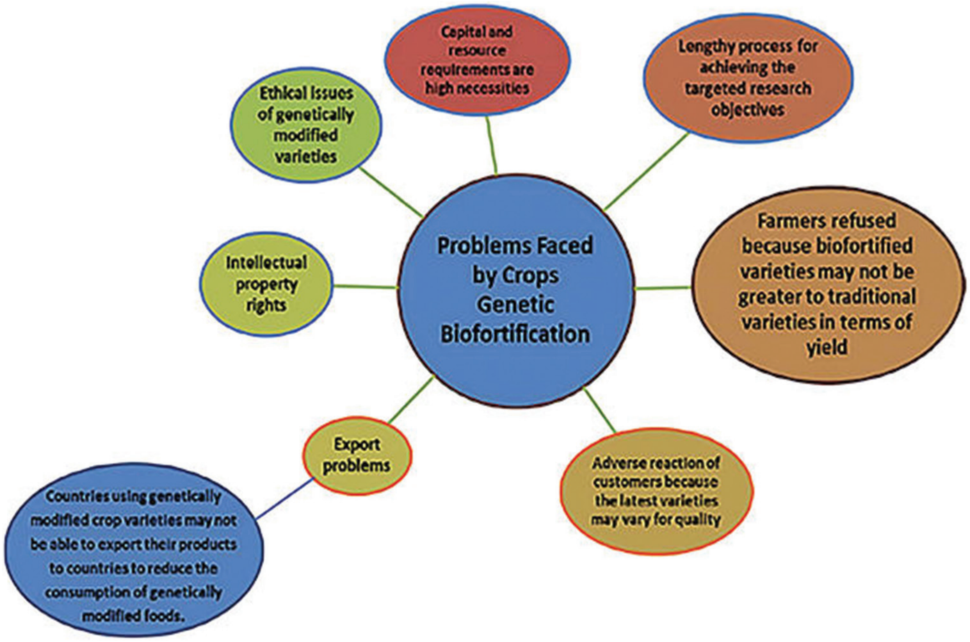

Figure 5: Challenges related to the genetic biofortification of crops[12]

Future perspectives

Emerging technologies enhance nutrient bioavailability through nanofertilizers

These advancements not only promise to enhance crop yields but also aim to minimize environmental impact by reducing the need for traditional chemical fertilizers. As agricultural practices evolve, the integration of smart farming techniques alongside these innovations can further optimize resource use and promote sustainable farming methods.[51] The combination of precision agriculture and advanced data analytics allows farmers to make informed decisions, tailoring their approach to the specific needs of their crops while maximizing efficiency and sustainability.[52]

Combine genetic, agronomic, and breeding strategies for zinc enrichment

These methods can enhance the bioavailability of Zn in crops, ultimately improving nutritional quality and addressing deficiencies in human diets. Implementing these integrated approaches not only boosts Zn levels in crops but also promotes sustainable agricultural practices that can lead to long-term food security and health benefits for populations at risk of micronutrient deficiencies.[53] Collaboration among researchers, farmers, and policymakers is essential to effectively implement these strategies, ensuring that the benefits of Zn enrichment reach those who need them most while fostering a resilient agricultural ecosystem. Engaging local communities in education and outreach initiatives will further empower stakeholders to adopt these practices, creating a more informed populace capable of advocating for their nutritional needs and contributing to the overall success of Zn enrichment programs. Such initiatives not only enhance crop yields but also encourage biodiversity and soil health, ultimately leading to more sustainable farming systems that can withstand the challenges posed by climate change.[54]

CONCLUSION

Addressing Zn deficiency through innovative agricultural practices is essential for improving community nutrition and health outcomes. The integration of various strategies, such as conventional and molecular breeding techniques, can lead to the development of high-Zn crop varieties that are resilient to environmental stresses and tailored to local conditions, thereby enhancing food security and nutritional quality. In addition, implementing sustainable practices like crop rotation and the use of ZSM can significantly improve Zn availability in soils, promoting better nutrient uptake and overall crop productivity. Furthermore, engaging local farmers in participatory breeding programs fosters a sense of ownership and ensures that new cultivars meet specific community needs while addressing market barriers is crucial for the dissemination of these innovations. Ultimately, a holistic approach that combines technical advancements with community engagement and education will be vital in combating Zn deficiency and enhancing the nutritional value of agricultural products, thereby contributing to the health and well-being of vulnerable populations.

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Ethics code

This is a review article, and no human or animal studies were conducted in its preparation; therefore, it does not require an ethics approval code.

Conflicts of interest

There are no conflicts of interest.

Authors' contributions

Amir Hossein Baghaie: Conceptualization, Investigation, Writing original draft; Ardeshir KhosraviDehkordi: Validation, Writing review and editing.

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