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Zinc enrichment strategies in legumes and cereals: Assessing current advancements and future prospects

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Abstract

Zinc, an indispensable micronutrient crucial for human health, plays a pivotal role in diverse physiological processes, encompassing immune function, growth, and cognitive development. Despite its profound significance, zinc deficiency remains a pressing global public health concern, particularly affecting populations heavily reliant on legumes and cereals as staple foods. This review paper delves into the importance of zinc fortification as an effective strategy to combat zinc deficiency in vulnerable populations. The review commences by examining the prevalence of zinc deficiency and its associated health implications, underscoring the challenges in attaining adequate zinc intake through conventional dietary practices. Inherent limitations in zinc content in staple foods, constraints in dietary diversity, and the prevalence of vegetarian diets are identified as major contributors to zinc deficiency. To address this nutritional concern, the significance of fortifying legumes and cereals with zinc is highlighted. Biofortification, fortification during processing, and genetic modification are explored as viable techniques to augment zinc content and bioavailability in these staple foods. Scientific evidence is presented to underscore the benefits of zinc-fortified legumes and cereals in ameliorating zinc status and related health outcomes. Vulnerable populations, including pregnant women, infants, and children, are shown to experience significant improvements in immune function, growth, and cognitive development through enhanced zinc intake. The review further examines future prospects and innovations in zinc fortification techniques. Emerging research in biofortification, nutrient-enhanced agronomy, and the potential of novel technologies, such as nanotechnology and biotechnology, offer promising avenues to effectively address zinc deficiency. However, the large-scale implementation of zinc fortification necessitates the overcoming of barriers and challenges. In conclusion, zinc fortification presents a potent and sustainable approach to enhance zinc nutrition and foster improved health outcomes for vulnerable populations worldwide. By integrating cutting-edge research, innovative technologies, and strategic interventions, the global community can work towards alleviating the burden of zinc deficiency and advancing public health. Continued efforts in research, policy support, and public engagement are crucial to fully realize the potential of zinc fortification in enhancing human health and well-being.

Keywords: Micronutrient deficiency, zinc fortification, cereal, legumes, dietary sources, bioavailability

1. Introduction

Micronutrients are essential for maintaining optimal human health, and among these, zinc plays a pivotal role in various physiological processes. It is classified as a trace mineral due to its requirement in minute quantities, yet its biochemical significance cannot be overstated (Islam *et al*., 2023) [41]. Zinc serves as a crucial cofactor for over 300 enzymes, participating in diverse biochemical reactions that are fundamental to cellular metabolism, growth, and development. One of the most prominent and well-studied aspects of zinc's role is its involvement in immune function (Chasapis *et al*., 2020) [16]. It plays a central role in both innate and adaptive immune responses, exerting influence on immune cell development, activation, and function. Zinc is critical for the differentiation and maturation of immune cells, such as T cells, B cells, and natural killer cells, thus impacting their ability to mount effective defenses against pathogens (Kim and Lee, 2021) [44]. Furthermore, zinc contributes to the maintenance of immune homeostasis by regulating cytokine production and modulating immune signaling pathways. Through these mechanisms, zinc deficiency can lead to immune dysregulation, rendering individuals more susceptible to infections and impairing the body's ability to combat pathogens (Kumar *et al*., 2022) [46]. Beyond its immunological significance, zinc is intimately involved in various aspects of skin health. The skin serves as a vital physical barrier, protecting the body from environmental insults and microbial invasions (Zou *et al*., 2023) [94]. Zinc is essential for the synthesis of collagen, a key structural protein that maintains the integrity of the skin and other connective tissues. As such, zinc deficiency can compromise the skin's barrier function, making individuals more vulnerable to skin infections and impairing wound healing processes (Souza *et al*., 2020) [83]. The influence of zinc on neurological function and cognitive processes is an area of growing research interest. Zinc is intricately involved in neurotransmitter synthesis and function, particularly in the modulation of excitatory and inhibitory neurotransmission. Through its interactions with glutamate and γ-aminobutyric acid (GABA) receptors, zinc contributes to synaptic plasticity, memory formation, and learning processes (Chakraborty, 2023) [15]. Additionally, zinc is a vital component of various enzymes and proteins involved in maintaining neuronal health and protecting against oxidative stress. Consequently, zinc deficiency has been associated with cognitive impairments, memory deficits, and mood disorders (Aslan *et al*., 2021) [7]. Zinc's significance during pregnancy and early childhood cannot be understated. It plays a pivotal role in DNA replication and cell division, processes critical for embryonic development and tissue growth. Adequate zinc intake during pregnancy is essential for optimal fetal growth and development, with implications for birth outcomes and long-term health (Marshall *et al*., 2022) [54]. Additionally, zinc is crucial for the proper development of the central nervous system during early childhood, shaping cognitive abilities and behavior. Despite its importance, zinc deficiency remains a global health concern, affecting a substantial portion of the population, particularly in low-resource settings (Amarasinghe *et al*., 2022) [3]. Inadequate dietary intake of zinc is often the primary cause of deficiency, exacerbated by factors such as poor food choices, limited access to diverse food sources, and underlying health conditions that hinder zinc absorption and utilization (Gupta *et al*., 2020) [32]. Addressing zinc deficiency requires a multifaceted approach. Public health interventions focused on improving dietary diversity and promoting the consumption of zinc-rich foods are essential. In cases where dietary approaches are insufficient, zinc supplementation may be considered under appropriate guidance and monitoring (Haile *et al*., 2022) [34]. However, it is crucial to strike a balance, as excessive zinc intake can also lead to adverse effects.

In conclusion, zinc is an indispensable micronutrient that plays multifaceted roles in maintaining human health. From supporting immune function and skin integrity to influencing neurological processes and aiding in early development, zinc's biological significance is profound. Understanding the scientific underpinnings of zinc's functions and the consequences of its deficiency empowers us to implement evidence-based strategies to combat zinc insufficiency and improve the overall health and well-being of populations worldwide. Further research in this area will undoubtedly contribute to refining our understanding of zinc's intricate roles and its potential as a therapeutic target for various health conditions.

2. Dietary Sources of Zinc: A Focus on Legumes and Cereals

Zinc, an essential trace mineral, plays a critical role in various physiological processes necessary for maintaining human health. From supporting immune function and enzymatic reactions to aiding in growth and development, zinc's multifaceted roles underscore its significance as a vital nutrient (Patil *et al*., 2023) [64]. While a diverse diet can provide adequate zinc intake, certain populations heavily reliant on legumes and cereals as staple foods may face challenges in meeting their zinc requirements (Okwuonu *et al*., 2021) [59]. This review aims to discuss the dietary sources of zinc, with a specific focus on legumes and cereals, shedding light on their potential as zinc contributors and exploring factors that impact zinc bioavailability from these food sources. Legumes and cereals are foundational components of diets in various cultures, providing essential nutrients to millions of people worldwide (Li *et al*., 2020) [49]. Despite their nutritional value, the bioavailability of zinc from these staple foods can be limited due to the presence of phytates. Understanding the dietary sources of zinc and adopting strategies to enhance zinc bioavailability in legumes and cereals is crucial for combatting zinc deficiency and promoting better overall health (Younas *et al*., 2022) [90]. By focusing on dietary diversification and implementing food processing techniques that optimize zinc uptake, we can improve the nutritional status and well-being of populations reliant on these staple foods.

Zinc, an essential trace mineral, is a fundamental component of numerous enzymatic and structural proteins, participating in diverse physiological processes critical for human health. These processes encompass immune function, DNA synthesis and repair, cell proliferation, and signal transduction (Silva *et al*., 2019) [78]. Zinc serves as a catalytic or structural cofactor for various enzymes, including zinc finger transcription factors, dehydrogenases, hydrolases, and kinases. As a result, zinc plays a pivotal role in regulating gene expression, maintaining redox balance, and supporting cell signaling pathways (Saha *et al*., 2020) [68]. The significance of zinc in immune function is well-established. Zinc deficiency has been shown to impair the development and functioning of both innate and adaptive immune cells. Mechanistically, zinc influences immune cell maturation, proliferation, and cytokine production, impacting immune responses against pathogens, tumor cells, and other challenges (Ramalho *et al*., 2020). Furthermore, zinc modulates the redox status of immune cells, influencing their capacity to mount an effective response to oxidative stress and infection. Zinc supplementation has been reported to enhance immune responses in zinc-deficient individuals and may have potential as an adjunct therapy for certain infections (Oyagbemi *et al*., 2021) [61].

2.1 Legumes as Zinc Sources

Legumes, including beans, lentils, chickpeas, and peas, constitute an essential part of the diet for numerous cultures worldwide. They offer a valuable source of plant-based protein, complex carbohydrates, fiber, and various micronutrients, including zinc (Semba *et al*., 2021) [73]. However, the bioavailability of zinc from legumes can be limited due to the presence of phytates, a naturally occurring compound that binds to zinc, making it less absorbable in the gut (Zhang *et al*., 2022) [89]. Soaking, sprouting, or fermenting legumes can help reduce phytate levels, improving zinc bioavailability and enhancing the nutritional value of these foods (Singh and Prasad, 2023) [78].

2.2. Cereals as Zinc Sources

Cereals, such as rice, wheat, maize, and millet, form the backbone of diets in many regions, providing a substantial proportion of daily caloric intake (Serna *et al*., 2020) [74]. While cereals contain zinc, they are also high in phytates, which inhibit zinc absorption. Additionally, the refining process of certain cereals, such as polished rice and refined wheat flour, further reduces zinc content (Gowda *et al*., 2022) [31]. As a result, populations heavily dependent on these staple cereals may be at risk of zinc deficiency. Promoting the consumption of whole grains, which retain the bran and germ layers, can help enhance zinc intake and availability (Gallego-Castillo *et al*., 2021) [29].

While various dietary sources provide zinc, plant-based foods, including legumes and cereals, constitute staple diets for many populations worldwide. Legumes, such as beans, lentils, chickpeas, and peas, are excellent sources of protein, dietary fiber, vitamins, and minerals, including zinc (Parveen *et al*., 2022) [63]. However, the presence of phytates in legumes can reduce zinc bioavailability by forming insoluble complexes with zinc ions in the gut, hindering their absorption. Various food processing methods, such as soaking, germination, and fermentation, have been shown to reduce phytate levels and improve zinc bioavailability from legumes.

Despite their importance, cereals often contain substantial amounts of phytates, which inhibit zinc absorption. Additionally, the refining processes used for certain cereals, such as polished rice and refined wheat flour, can further reduce their zinc content. Encouraging the consumption of whole grains, which retain the bran and germ layers, can contribute to higher zinc intake and bioavailability (Aiqing *et al*., 2022) [2].

To enhance zinc bioavailability from legumes and cereals, several dietary approaches can be adopted. Co-consuming foods rich in organic acids or vitamin C, such as fruits and vegetables, can facilitate zinc uptake by chelating phytate and promoting zinc solubility (Bhantana *et al*., 2021) [11]. Moreover, the combination of plant-based sources with animal-derived foods, such as meat and dairy products, can enhance zinc absorption, as animal proteins are sources of sulfur-containing amino acids that increase zinc availability (Fu *et al*., 2022) [28]. Additionally, various food processing techniques, such as fermentation and germination, can degrade phytates and activate endogenous phytase enzymes, further increasing zinc bioavailability (Sarkhel *et al*., 2022) [71].

Understanding the dietary sources of zinc and the factors influencing its bioavailability is of utmost importance, particularly in regions where legumes and cereals form the dietary foundation. Zinc deficiency can have profound implications for human health, affecting immune function, growth, and cognitive development. Implementing dietary strategies to maximize zinc uptake from plant-based staples can be instrumental in combatting zinc deficiency and promoting overall health and well-being in vulnerable populations. Further research and public health interventions focusing on dietary diversification and optimizing zinc bioavailability are essential in addressing this global nutritional concern.

3. Factors Influencing Zinc Bioavailability and Absorption

Zinc, an essential micronutrient, serves as a cofactor for numerous enzymes and transcription factors, participating in critical cellular processes such as DNA replication, RNA transcription, and protein synthesis (Hassan *et al*., 2020) [36]. The acquisition of sufficient zinc from the diet is essential for maintaining optimal human health. However, achieving adequate zinc bioavailability and absorption is a complex process influenced by multiple factors that intricately regulate zinc uptake in the gastrointestinal tract (Li *et al*., 2023) [48]. This comprehensive review aims to elucidate the key determinants affecting zinc bioavailability and absorption, providing insights into the molecular and physiological mechanisms of zinc metabolism. By understanding these factors, researchers, healthcare professionals, and policymakers can develop targeted strategies to combat zinc deficiency and promote better nutritional outcomes and overall health.

3.1 Dietary Composition

The composition of the diet plays a pivotal role in determining zinc bioavailability. Foods rich in phytates, such as legumes, cereals, and some nuts, can form insoluble complexes with zinc, diminishing its solubility and availability for absorption (Katimba *et al*., 2023) [41]. Similarly, dietary fiber can chelate zinc, reducing its bio-accessibility. Conversely, dietary components like animal proteins, particularly from meat and seafood, can enhance zinc absorption by forming soluble complexes with zinc ions in the digestive milieu (Silva *et al*., 2019) [78].

3.2. Zinc Content in the Diet

The absolute amount of zinc present in the diet is a crucial factor governing zinc absorption efficiency. In situations of zinc scarcity, the body enhances zinc uptake to meet its physiological requirements (Gupta *et al*., 2020) [32]. Conversely, in the context of a high-zinc diet, zinc absorption rates decrease as a homeostatic mechanism to prevent zinc overload. Nonetheless, the intricate interplay between zinc intake and absorption efficiency can lead to divergent zinc statuses in different individuals (Suganya *et al*., 2020) [80].

3.3 Zinc Status and Physiological Needs

The body's zinc status and physiological demands dynamically influence zinc absorption rates. During periods of heightened zinc requirements, such as growth, pregnancy, lactation, or infection, the body upregulates zinc transporters in the enterocytes, enhancing zinc uptake from the diet (Maares and Hssae, 2020) [52]. Conversely, when zinc levels are replete, the body downregulates zinc absorption to avoid excess accumulation and potential toxicity (Chinni *et al*., 2021) [18].

3.4 Age and Developmental Stage

Age-related variations in zinc absorption efficiency exist due to varying physiological demands during different life stages (Li *et al*., 2022) [50]. Infants and adolescents, characterized by rapid growth and development, exhibit higher zinc absorption rates to support tissue expansion and cellular proliferation (Donker *et al*., 2021) [21]. Infants, in particular, display higher efficiency of zinc absorption from breast milk compared to formula milk. However, as individuals age, zinc absorption efficiency may decline, contributing to the increased prevalence of zinc deficiency in older adults (Wong *et al*., 2021) [86].

3.5 Gut Health and Disorders

The integrity and health of the gastrointestinal tract significantly influence zinc bioavailability. Conditions affecting stomach acid secretion, such as achlorhydria, or disorders that disrupt the absorptive capacity of the small intestine, including celiac disease and inflammatory bowel diseases, can impair zinc absorption (Gorey, 2022) [30]. Additionally, certain medications and medical procedures, such as antacids or bariatric surgery, may alter zinc uptake.

3.6 Genetic Factors

Genetic determinants play a crucial role in zinc absorption and transport. Mutations in zinc transporters, such as ZIP4 and ZnT1, have been associated with inherited zinc deficiency disorders (Ohashi *et al*., 2019) [58]. Polymorphisms in genes involved in zinc metabolism can also contribute to inter-individual variations in zinc status.

3.7 Food Processing and Preparation

Food processing techniques significantly impact zinc bioavailability. For instance, certain processing methods, such as soaking, germination, and fermentation of grains and legumes, can reduce phytate content, enhancing zinc uptake (Elliot *et al*., 2022) [24]. Conversely, refining processes like polishing rice or milling wheat remove the nutrient-rich outer layers, decreasing zinc content.

A comprehensive understanding of the factors influencing zinc bioavailability and absorption is crucial for devising effective strategies to combat zinc deficiency and improve overall health. The intricate interactions between dietary composition, zinc content, physiological needs, age, gut health, genetics, and food processing underscore the complexity of zinc metabolism. By considering these multifaceted factors, researchers, healthcare professionals, and policymakers can develop evidence-based interventions and public health initiatives to address zinc deficiency and promote better nutritional outcomes across diverse populations. Further research in this domain will continue to enhance our knowledge of zinc metabolism and its implications for human health and well-being.

4. Challenges in achieving adequate zinc intake through conventional dietary practices

Zinc, an indispensable micronutrient, plays a pivotal role in numerous physiological processes, encompassing immune function, growth, DNA synthesis, and enzymatic activities (Weyh *et al*., 2022) [85]. Despite its critical significance in maintaining human health, attaining sufficient zinc intake through conventional dietary practices can prove arduous for specific population groups (Marshall *et al*., 2022) [54]. This review aims to comprehensively examine the multifaceted challenges impeding optimal zinc intake via traditional diets, shedding light on the barriers to achieving adequate zinc nutrition and their implications for public health.

4.1 Low Zinc Content in Staple Foods

Numerous populations heavily rely on staple foods, such as cereals and legumes, as their primary sources of caloric intake. However, these dietary staples often exhibit inherently low zinc content (Semba *et al*., 2021) [73]. For instance, cereals and grains contain phytates that hinder zinc absorption, while legumes may possess low levels of bioavailable zinc due to the presence of anti-nutrients like phytates and fibers. Consequently, individuals predominantly consuming these staple foods may face difficulties in meeting their daily zinc requirements (Praharaj *et al*., 2021) [65].

4.2 Limited Dietary Diversity

In certain regions, conventional dietary practices may lack diversity, resulting in inadequate intake of zinc-rich foods. Populations primarily adhering to monotonous diets, with limited inclusion of animal products, fruits, vegetables, and nuts, face a higher risk of zinc deficiency. This lack of dietary diversity can further compound the challenges associated with zinc bioavailability, as the combination of different foods is essential for optimizing zinc uptake (Modjadji *et al*., 2020) [55].

4.3 Vegetarian and Vegan Diets

Vegetarian and vegan diets, while healthful, may pose challenges in meeting zinc requirements. Plant-based foods are not as abundant in bioavailable zinc as animal-derived sources. Moreover, plant foods frequently contain phytates and other compounds that hinder zinc absorption. While var ious strategies, such as food pairing and processing techniques, can enhance zinc bioavailability, individuals following vegetarian and vegan diets must be particularly mindful of their dietary choices to ensure sufficient zinc intake (Thakur *et al*., 2019) [82].

4.4 Inadequate Zinc Supplementation and Fortification

In regions where zinc deficiency is prevalent, conventional dietary practices alone may prove insufficient to meet the population's zinc needs. Nevertheless, access to zinc supplements and fortified foods may be limited, especially in low-income settings (Otunchieva *et al*., 2022) [60]. Ensuring widespread availability of affordable and accessible zinc supplements and fortified products presents a logistical challenge for public health initiatives.

4.5 Nutritional Knowledge and Awareness

Limited nutritional knowledge and awareness about the importance of zinc and its food sources can also impede adequate zinc intake. A lack of understanding about zinc-rich foods, their preparation, and factors affecting zinc bioavailability can lead to dietary choices that do not effectively meet zinc needs (Mohamad *et al*., 2023) [56]. Enhancing nutritional education and awareness programs is crucial to empower individuals to make informed decisions about their diets.

4.6 Socioeconomic Factors

Socioeconomic disparities can significantly impact zinc intake. Low-income populations may encounter barriers in accessing diverse and nutrient-rich foods, resulting in zinc-deficient diets. Additionally, zinc-rich animal products may be more expensive, rendering them less accessible to economically disadvantaged individuals (Ebi *et al*., 2021) [22].

Achieving sufficient zinc intake through conventional dietary practices presents a complex challenge influenced by multiple factors, including low zinc content in staple foods, limited dietary diversity, vegetarian and vegan diets, inadequate supplementation and fortification, lack of nutritional knowledge, and socioeconomic disparities. Addressing these challenges necessitates a comprehensive approach involving public health interventions, nutritional education, fortification programs, and policies promoting diverse and zinc-rich diets. By overcoming these obstacles, researchers, policymakers, and healthcare professionals can collaborate to improve zinc nutrition and reduce the burden of zinc deficiency-related health issues in vulnerable populations (Freeman *et al*., 2023) [27].

In the pursuit of combatting zinc deficiency and bolstering public health, fortification of staple foods such as legumes and cereals has emerged as a promising strategy. Fortification entails augmenting the nutrient content of foods to address specific nutritional deficiencies. In the case of zinc fortification, diverse methodologies have been developed to elevate the zinc content and bioavailability of these fundamental dietary staples. This review aims to present an overview of current zinc fortification techniques, encompassing biofortification, fortification during processing, and genetic modification, while focusing on their efficacy and potential implications for global health.

5. Utilization of different techniques for the Fortification of legumes and cereals

5.1 Biofortification

Biofortification involves a natural approach to elevate the nutrient levels of crops through the selection or breeding of varieties with elevated zinc concentrations. Plant breeding techniques aim to enhance zinc uptake and translocation within the plant, ultimately leading to zinc-enriched edible components (Dhaliwal *et al*., 2022) [20]. This method offers notable advantages in regions where zinc deficiency prevails, as it provides a sustainable and cost-effective means of improving the nutritional quality of staple crops.

For instance, in rice, a staple food for approximately half of the global population, biofortification efforts have successfully yielded zinc-enhanced varieties via traditional breeding practices. These biofortified rice varieties exhibit heightened zinc content in the polished grains, effectively addressing deficiencies in rice-consuming communities.

5.2 Fortification during Processing

Fortification during processing entails the addition of zinc or zinc-containing compounds to staple foods during their production or preparation (Baldelli *et al*., 2021) [9]. This technique is widely employed for mass-scale fortification, as it enables precise control over zinc levels in the final product. The incorporated zinc should be in a bioavailable form, ensuring its effective absorption by the human body (Barone *et al*., 2022) [10].

In the case of wheat flour fortification, zinc can be added as zinc sulfate, zinc oxide, or other zinc salts. Similarly, in maize and rice fortification, zinc-containing compounds are mixed with the grains during milling. This approach has proven successful in various countries, where fortified flours are utilized to produce widely consumed foods such as bread, noodles, and biscuits.

5.3 Genetic Modification

Genetic modification, or genetic engineering, involves direct manipulation of an organism's genome to introduce specific traits (Saravanan *et al*., 2022) [70]. While this approach shows potential for enhancing zinc content in crops, it remains subject to debate due to concerns regarding safety, ethics, and consumer acceptance. Researchers have explored the possibility of genetically modifying crops to express genes associated with increased zinc uptake and transport within plant tissues. By introducing genes encoding zinc transporters, plants can accumulate higher zinc concentrations in their edible parts. However, further research and regulatory approvals are necessary before genetically modified zinc-fortified crops can be widely adopted (Hirschi, 2020) [37].

Zinc fortification of legumes and cereals represents a pivotal stride in addressing zinc deficiency and advancing public health. Biofortification offers a sustainable and natural approach, while fortification during processing provides an efficient method for large-scale implementation (Kiran *et al*., 2022) [44]. Genetic modification holds promise for generating crops with enhanced zinc content, but its broader adoption necessitates careful consideration of ethical, safety, and regulatory aspects. The amalgamation of these fortification techniques with educational initiatives and nutritional awareness programs can further augment their impact on vulnerable populations (Abdul Aziz *et al*., 2022) [1]. Through the judicious utilization of these current zinc fortification methods, researchers, policymakers, and healthcare professionals can collaboratively work towards enhancing zinc nutrition and mitigating the burden of zinc deficiency-related health issues worldwide.

5.4 Impact of Zinc Fortification on Human Health

Zinc fortification of staple foods, such as legumes and cereals, has emerged as a promising strategy to combat zinc deficiency and its associated health consequences (Hussain *et al*., 2022) [38]. This review aims to provide a scientific summary of the evidence on the benefits of zinc-fortified legumes and cereals on human health, with a specific focus on the improvements in zinc status and related health outcomes observed in vulnerable populations.

6. The effectiveness of each technique in enhancing zinc content and bioavailability

Scientific studies have consistently demonstrated the effectiveness of zinc fortification in enhancing zinc status among individuals consuming fortified foods. Biofortified crops, developed through traditional breeding techniques, have shown higher zinc concentrations in their edible parts, making them suitable dietary sources of bioavailable zinc (Buturi *et al*., 2021) [14]. Fortification during processing, involving the addition of zinc or zinc-containing compounds, has also proven successful in increasing zinc content in staple foods. Consumption of zinc-fortified legumes and cereals has led to significant improvements in zinc intake and absorption, ultimately elevating zinc levels in the body (Waqeel *et al*., 2022) [84]. Populations heavily reliant on these staple foods have exhibited marked increases in plasma zinc concentrations and zinc-related biomarkers following the incorporation of fortified foods into their diets.

6.1 Improvements in Immune Function

Zinc plays a crucial role in supporting immune function, and zinc deficiency is associated with impaired immune response and increased susceptibility to infections. Zinc fortification has shown promising effects on immune function, particularly in vulnerable populations (Kim and Lee, 2021) [44]. Scientific studies have reported reduced rates of infections, shortened duration of illnesses, and improved immune response in children and adults consuming zinc-fortified foods (Arfi *et al*., 2022) [5]. Fortification has proven effective in enhancing both innate and adaptive immune responses, leading to better defense against pathogens and improved overall health.

6.2 Growth and Development

Zinc is essential for growth and development, particularly during critical periods such as pregnancy, lactation, and childhood. Adequate zinc intake is crucial for fetal development, ensuring healthy birth outcomes and optimal cognitive development in children (Mousa *et al*., 2019) [57]. viZinc fortification has demonstrated positive effects on growth parameters, such as height and weight, in children and adolescents. Pregnant and lactating women consuming fortified foods have shown improvements in birth weight and a reduced risk of low birth weight babies (Parker *et al*., 2021) [62]. Additionally, zinc-fortified diets have been associated with better cognitive development and improved learning outcomes in children.

6.3 Cognitive Function

Zinc deficiency has been linked to impaired memory, attention, and learning abilities. Fortifying staple foods with zinc has shown promising effects on cognitive function, particularly in populations at risk of zinc deficiency. Scientific studies have reported improvements (Kumari *et al*., 2022) [46] in memory, attention, and cognitive performance in children and adults following zinc fortification. These findings underscore the potential of fortification as a cost-effective and scalable intervention to address cognitive impairments associated with zinc deficiency.

Zinc fortification of legumes and cereals has been scientifically proven to be an effective strategy in improving zinc status and related health outcomes among vulnerable populations. The scientific evidence supports the benefits of zinc-fortified foods in enhancing immune function, promoting growth and development, and improving cognitive function (Chemek *et al*., 2023) [17]. Incorporating zinc-fortified staple foods into the diet has the potential to alleviate zinc deficiency and its adverse health effects, leading to better overall health and well-being in populations at risk of zinc deficiency (Evan, 2023) [25]. Continued scientific research, monitoring, and advocacy are essential to ensure the successful implementation and sustained impact of zinc fortification programs worldwide.

7. Potential Implications for Vulnerable Populations: Pregnant Women, Infants, and Children

Zinc fortification of staple foods, such as legumes and cereals, holds significant potential to address zinc deficiency and improve health outcomes, particularly among vulnerable populations, including pregnant women, infants, and children (Haridas *et al*., 2022) [35]. Understanding the implications of zinc fortification for these groups is essential for guiding effective public health strategies and interventions. Here, we discuss the potential implications for each vulnerable population. During pregnancy, zinc plays a critical role in supporting fetal development and maternal health (Iqbal and Ali, 2021) [39]. Adequate zinc intake is essential for proper embryogenesis, placental function, and overall growth of the fetus. Zinc deficiency during pregnancy can lead to complications such as low birth weight, preterm birth, and impaired cognitive development in the child (Kibr, 2021) [42]. Zinc fortification can offer significant benefits for pregnant women by increasing their zinc intake and status. Improved zinc levels can positively impact fetal growth, reducing the risk of low birth weight and associated health complications. Additionally, adequate zinc intake during pregnancy can contribute to better immune function, reducing the susceptibility of both the mother and child to infections (Suliman *et al*., 2020) [81]. Infancy is a critical period of rapid growth and development, during which zinc plays a crucial role in numerous physiological processes. Breast milk provides essential nutrients, including zinc, to support the infant's optimal development. However, in regions where breastfeeding practices may be suboptimal or when breast milk zinc levels are insufficient, infants may be at risk of zinc deficiency. Zinc-fortified complementary foods can be vital for infants transitioning to solid foods, as they help ensure adequate zinc intake during this crucial stage (Brion *et al*., 2021) [13]. Fortified infant cereals and other complementary foods can support the infant's nutritional needs and promote healthy growth and development. Proper zinc intake can also enhance the infant's immune system, reducing the risk of infections and promoting overall well-being (Ayivi *et al*., 2021) [8]. Children's health and development are profoundly affected by their nutritional status, including zinc intake. Zinc is essential for immune function, cognitive development, and physical growth during childhood. Zinc deficiency in children can lead to stunted growth, increased susceptibility to infections, and impaired cognitive abilities. Zinc fortification of staple foods in children's diets can significantly improve their zinc status, leading to better growth and development outcomes (Tsang *et al*., 2021) [83]. Fortified cereals and other food products can help bridge nutritional gaps, especially in regions where dietary diversity may be limited. Enhanced zinc intake can support immune function, reducing the frequency and severity of infections, which can contribute to better school attendance and academic performance. Zinc fortification of staple foods has far-reaching implications for vulnerable populations, including pregnant women, infants, and children (Ara *et al*., 2019) [4]. By addressing zinc deficiency in these groups, fortification can contribute to improve maternal and child health outcomes, reduced risk of low birth weight and stunting, and enhanced immune function. The benefits of zinc fortification extend beyond individual health, positively impacting public health, healthcare systems, and economic productivity. Continued research, targeted interventions, and nutritional education are essential to maximize the potential benefits of zinc fortification and ensure better health outcomes for vulnerable populations worldwide.

8. Future Prospects and Innovations in Zinc Fortification Techniques

As the significance of zinc fortification in addressing zinc deficiency and related health implications gains recognition, the field of research and innovations in fortification techniques is continuously evolving. This section sheds light on emerging trends and novel technologies that hold promise in enhancing zinc content and bioavailability in legumes and cereals. Additionally, potential strategies to overcome barriers and challenges for large-scale implementation are discussed.

9. Emerging Research and Innovations

9.1 Biofortification Advancements

Biofortification research continues to focus on developing crop varieties with enhanced zinc accumulation. Advances in molecular breeding techniques and genomics have enabled scientists to identify genes and traits associated with increased zinc uptake and translocation within plants (Fiaz *et al*., 2021)

[26]. Precision breeding approaches are being employed to introduce these traits into staple crops, such as rice, wheat, and maize, to develop zinc-rich varieties that can effectively address regional deficiencies (Sharma *et al*., 2023) [75].

9.1.1 Nutrient-Enhanced Agronomy

Innovations in agronomic practices are being explored to improve zinc uptake by plants from the soil (Ashraf *et al*., 2021) [6]. Optimizing soil management, including pH adjustments and micronutrient fertilization, can enhance zinc bioavailability for plant uptake, leading to increased zinc content in harvested crops.

9.2 Potential of Novel Technologies

9.2.1 Nanotechnology

Nanotechnology holds great potential in enhancing zinc fortification by improving the bioavailability of zinc in staple foods (Elemike *et al*., 2019) [23]. Encapsulation of zinc compounds in nano-sized particles can protect zinc from interactions with inhibitory compounds in the gastrointestinal tract, increasing its absorption. Nanoparticles can also be designed to release zinc gradually, ensuring sustained bioavailability and utilization by the body (Shelar *et al*., 2023) [76].

9.2.2 Biotechnology

Biotechnological approaches, such as genetic engineering, offer possibilities to manipulate zinc transporters and other relevant genes within plant genomes (Hafeez *et al*., 2023) [33]. By enhancing the expression of genes involved in zinc uptake and translocation, genetically modified crops can accumulate higher levels of bioavailable zinc in their edible parts (Kumar *et al*., 2019) [47].

10. Strategies to Overcome Barriers and Challenges

10.1 Collaboration and Advocacy

Effective implementation of zinc fortification programs requires collaboration among governments, non-governmental organizations, research institutions, and the food industry. Advocacy efforts can raise awareness about the importance of zinc fortification, leading to supportive policies and funding for large-scale initiatives (Mkambula *et al*., 2020) [54].

10.2 Cost-Effectiveness and Sustainability

Strategies to fortify legumes and cereals with zinc should be economically viable and sustainable in the long term (Sangeetha *et al*., 2022) [69]. Integrating fortification into existing food processing and distribution systems can ensure cost-effectiveness and continuity of zinc-enhanced food availability.

10.3 Nutrition Education and Awareness

Public awareness and nutritional education are crucial in promoting acceptance and adoption of zinc-fortified foods. Informing communities about the benefits of zinc fortification and how to prepare and consume fortified products optimally can lead to higher uptake and sustained improvements in zinc intake (Lowe, 2021) [51].

Future prospects and innovations in zinc fortification techniques offer exciting possibilities to combat zinc deficiency and its associated health challenges. Emerging research in biofortification, nutrient-enhanced agronomy, nanotechnology, and biotechnology shows promise in enhancing zinc content and bioavailability in legumes and cereals (Bisht *et al*., 2021) [12]. However, large-scale implementation necessitates collaborative efforts, cost-effectiveness, and nutritional education to overcome barriers and ensure sustained impact on public health (Sarma, 2021) [72]. By embracing novel technologies and adopting strategic approaches, stakeholders can work towards improving zinc nutrition and contributing to healthier, more resilient communities worldwide.

11. Conclusion

In conclusion, zinc fortification of staple foods, particularly legumes and cereals, emerges as a critical and promising strategy to address zinc deficiency and its implications on human health. Throughout this review, we have explored the significance of zinc as a vital micronutrient and the prevalence of zinc deficiency, especially in populations heavily reliant on legumes and cereals as staple foods. Understanding the dietary sources of zinc, we highlighted the challenges in achieving adequate zinc intake through conventional dietary practices. Limited zinc content in staple foods, dietary diversity constraints, and vegetarian diets were identified as key factors contributing to zinc deficiency in vulnerable populations. To tackle this nutritional concern, we emphasized the significance of fortifying legumes and cereals with zinc. Biofortification, fortification during processing, and genetic modification were discussed as effective techniques to enhance zinc content and bioavailability in these staple foods. Scientific evidence supports the benefits of zinc-fortified legumes and cereals in improving zinc status and related health outcomes. Vulnerable populations, including pregnant women, infants, and children, stand to gain significantly from zinc fortification initiatives. Enhanced zinc intake can lead to better immune function, improved growth and development, and enhanced cognitive performance. Moreover, future prospects and innovations in zinc fortification techniques hold great promise. Emerging research in biofortification and nutrient-enhanced agronomy, as well as the potential of novel technologies like nanotechnology and biotechnology, open new avenues to address zinc deficiency more effectively. Nevertheless, large-scale implementation of zinc fortification requires overcoming barriers and challenges. Collaboration among stakeholders, cost-effectiveness, and sustainability in implementation, and targeted nutritional education and awareness are key strategies to ensure the success and widespread impact of zinc fortification programs. In conclusion, zinc fortification presents a powerful tool to improve zinc nutrition and promote better health outcomes for vulnerable populations worldwide. By integrating cutting-edge research, innovative technologies, and strategic interventions, we can work towards alleviating the burden of zinc deficiency, ultimately contributing to healthier and more resilient communities globally. Continued efforts in research, policy support, and public engagement are vital to realize the full potential of zinc fortification in enhancing human health and well-being.

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13. Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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