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Unlocking the Potential of Zinc Efficiency for Enhanced Crop Production in Low Zinc Environments

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ABSTRACT

Background: *An estimated three billion people worldwide suffer from deficiencies in zinc (Zn) and iron (Fe), resulting in the death of 500,000 children every year. As the global shift towards healthier diets continues, the importance of essential mineral nutrients, especially Zn, becomes more pronounced.* ***Objective:*** *To provide a comprehensive insight into the critical aspects of Zn efficiency in plants, especially in terms of uptake, transport, and utilization, to address global nutritional needs.* ***Methods****: Zn plays a vital role in multiple plant processes, including enzyme activation, chlorophyll synthesis, gene expression, signal transduction, and defense.* ***Results:*** *Zn deficiency, especially in alkaline soils, is a widespread issue, impacting crop yield and growth. Increasing Zn efficiency in plants involves optimizing Zn uptake, transport, and utilization. Focusing on the cultivation of crops like rice, beans, wheat, soybeans, and maize, which inherently have a robust ability to absorb and utilize Zn, can be instrumental in ensuring sustainable food production. The review delves into the root system's capability in Zn absorption, the contribution of Zn transporters, and the importance of Zn utilization in the shoot system.* ***Conclusion:*** *Enhancing Zn efficiency in crops is paramount in addressing global nutritional deficiencies, promoting sustainable food production, and ensuring a brighter future with food security for all.*

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INTRODUCTION

Zinc, as a critical micronutrient, plays a crucial role in various vital physiological and biochemical processes in plants, such as those associated with photosynthesis, respiration, and hormone metabolism [1]. Despite the significance of zinc, soil deficiency of this micronutrient is a prevalent issue that hampers crop productivity in numerous regions worldwide. Zinc, being an essential micronutrient, plays a critical role in the growth and development of plants, as well as in various physiological and biochemical processes [2]. Despite its crucial role, widespread soil Zn deficiency has a detrimental impact on crop productivity. This meta-analysis review paper seeks to bring attention to the significance of zinc efficiency for the future of crop production in regions characterized by suboptimal zinc conditions [3]. In this paper, we aim to give a

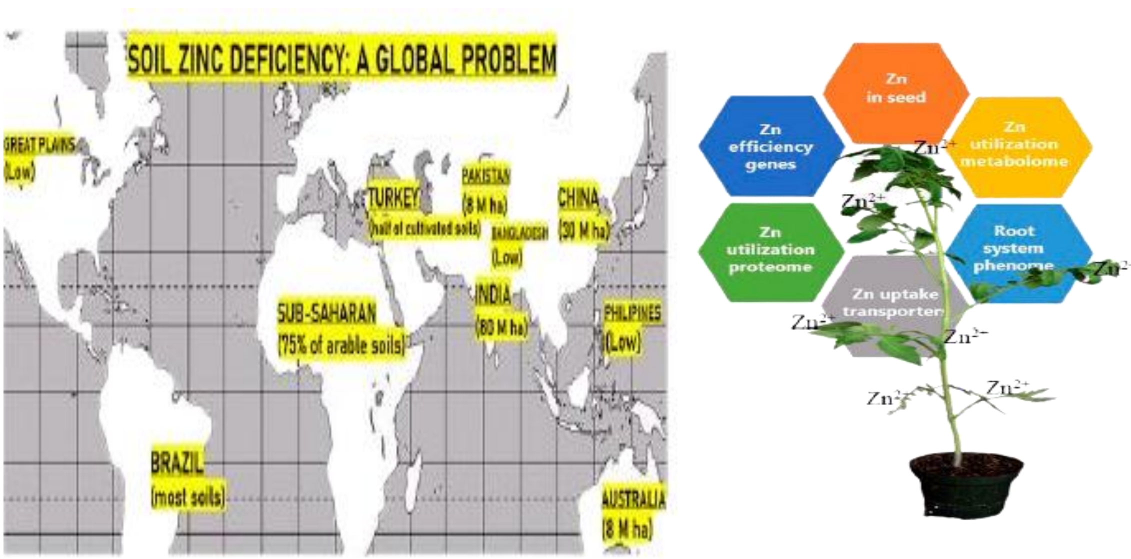

Figure 1. A brief summary of Zinc Deficiency and its impact on plants, including: (a) a map of the world highlighting major regions and countries with soil lacking in Zinc, (b) potential strategies for increasing plant efficiency in obtaining Zinc[4].

overview of the issue of soil Zn deficiency, showcasing the evidence of naturally occurring genetic variation in terms of zinc efficiency in plants [4]. Additionally, we delve into various zinc efficiency strategies implemented in crop plants and examine the underlying mechanisms of zinc efficiency, including the zinc uptake systems and transporters, utilization of zinc within the shoot, and other relevant mechanisms. We conclude by highlighting future challenges and perspectives in the field. The objective of this review paper is to highlight and summarize the latest advancements and research findings related to zinc efficiency and its potential impact on future crop production under suboptimal zinc conditions. Projections estimate that by the year 2050, the world's population will reach a staggering 10 billion, which means that in order to meet the food demands of this growing population, global food crop production must significantly increase and double in quantity [5]. Zinc deficiency is a widespread nutritional disorder that poses a significant threat, particularly in developing countries, with an estimated 17.3% of the world's population at risk of being affected by this condition [6]. Zinc, being an essential mineral, plays a critical role in various plant processes that are vital to the growth, development, and overall functioning of the plant. These processes include enzyme formation, photosynthesis, protein synthesis, and signal transduction [7]. However, soil Zn deficiency affects over 49% of arable lands globally, negatively impacting plant growth and crop yield [8]. In Zn-deficient countries like Turkey, Australia, Brazil, India, and China, there is a significant focus on conducting research and developing crops that are more efficient in terms of zinc utilization. This is being done with the aim of reducing yield losses and maximizing productivity in these regions [9-10]. Another important aspect of increasing zinc efficiency is improving the zinc content in staple food crops like rice, wheat, maize, and beans. This can be done through techniques such as biofortification, which is crucial for ensuring adequate human nutrition and promoting healthy development. This review focuses on the strategies plants use to cope with low Zn availability and the advancements in Zn efficiency research, including future directions [11].

Zinc may be the last element in the list of essential nutrients, but it is by no means any less important. This mineral is crucial for the growth and proper functioning of plants, as well as human nutrition through the consumption of plant-based foods [12]. Ongoing research is constantly improving our understanding of the significance of zinc and its impact. This includes exploring the characteristics of crop varieties that are able to grow and prosper in soil conditions that are deficient in zinc [13].

The exploration of Zn efficiency strategies, cellular mechanisms, and genes holds the potential to advance agricultural sustainability, enhance human nutrition, and reduce the reliance on synthetic fertilizers. A thorough understanding of these aspects can lead to significant advancements and improvements. Improved Zn efficiency in crops can lead to enhanced crop production and better nutritional quality, which will be essential in meeting the needs of an increasing global population [14].

In order to further expand our understanding of Zinc (Zn) efficiency, a number of areas require further research. Future studies should aim to pinpoint the specific genes and processes involved in zinc efficiency in plants, make use of advanced genome editing tools such as CRISPR-Cas9, enhance the measurement of zinc efficiency in food crops, analyze the metabolic changes that occur in response to low zinc conditions through metabolomic profiling, and investigate the genetic factors contributing to zinc efficiency and the accumulation of seed zinc under low zinc conditions through genome-wide association studies. By exploring these avenues of research, we can contribute to the improvement of agricultural sustainability, human nutrition, and the reduction of the need for synthetic fertilizers.

Zinc Deficiency in Soil:

To ensure that crops are able to grow and flourish, they require a range of nutrients, including zinc (Zn). Since 1926, zinc, a type of divalent cation, has been widely recognized as a crucial micronutrient for higher green plants. Nonetheless, various soil types can suffer from zinc deficiency, hindering the growth and output of crops. Such soil types include those with limited zinc availability, soils with high pH and high levels of calcium, those that have undergone extensive farming, sandy soils, and soils with high levels of phosphorus [15]. It's estimated that a significant portion of the world's soils, about 50%, have low levels of zinc naturally. This lack of zinc in the soil can lead to deficiencies in crops and impact their growth and productivity. As zinc is an essential micronutrient for plant growth, it's important to study ways to improve zinc efficiency in crops to ensure sustainable food production for a growing population [16]. It is well-known that a large percentage of soils worldwide are affected by Zn deficiency, leading to reduced crop production. However, the exact extent of this issue varies from region to region, with some areas being particularly hard hit. Despite this, a comprehensive understanding of the issue and ongoing research efforts aim to address this challenge and improve agricultural sustainability for farmers and communities around the world [17]. Zinc (Zn) is an indispensable micronutrient that holds a key place in ensuring the well-being and development of crops. Zinc deficiency can arise in several soil types, including those with low zinc availability such as soils with high pH and high levels of calcium, soils that have undergone extensive farming, sandy soils, and soils with high levels of phosphorus. While zinc deficiency is a widespread issue in many developing countries, it is also a concern in developed nations, such as the United States. For instance, zinc deficiency is prevalent in the Great Plains and western regions of the US as well as in sandy soils in Florida. However, the exact extent of Zn-deficiency in these regions is still being studied [18]. To ensure that crops are able to grow and thrive in soil conditions with low levels of zinc (Zn), identifying and cultivating varieties that are efficient in utilizing the mineral is a more favorable approach than solely relying on synthetic fertilizers. This approach helps to minimize any adverse effects on yield and quality that can occur as a result of Zn deficiency in the soil [19]. Screening of crops like wheat, beans, chickpeas, and rice to identify Zn-efficient genotypes is a critical step in managing low-Zn soil stress and reducing yield and quality losses. For this purpose, numerous genotypes of these crops have undergone assessment to determine their Zn efficiency. The process of evaluating crops for zinc efficiency involves a comprehensive analysis that includes analyzing their visual symptoms and assessing the impact on their biomass and yield under conditions of both low and sufficient zinc levels [4]. The technology of phenotyping, which is the process of evaluating physical and biological traits of an organism, has come a long way in recent times. This advancement has the potential to bring about improvements in the way zinc efficiency is evaluated and predicted [20]. The cultivation of Zn-efficient cereal and vegetable cultivars is a crucial step towards a more sustainable agriculture and ensuring sufficient food supply for growing populations. By minimizing the need for synthetic fertilizers and increasing crop yields, Zn-efficient crops play a significant role in meeting the global demand for food [21].

Soil Zn insufficiency is a global challenge that has a significant impact on agricultural yields across various regions. It happens when there is not enough Zn in the soil to support healthy growth and development of plants [22]. There are a number of factors that can cause soil zinc deficiency, including low soil pH, excessive amounts of phosphorus, and overuse of other micronutrients. These factors can result in insufficient zinc availability for optimal plant growth and development, a problem that is prevalent in many regions around the world [23]. The severity of soil Zn deficiency varies depending on the soil type and management practices [24].

Natural Genetic Variation in Plants for Zinc Efficiency: Evidence

To achieve successful crop production and avoid economic loss, researchers are exploring ways to address soil Zn deficiency which can negatively impact yields. This includes the study of beneficial alleles and the investigation of natural variation in Zn efficiency through association studies [24]. The natural variation in Zn efficiency in crops is of great importance for crop breeding and selection, as this variation can impact crop yields. Some crops are known to be Zn efficient, such as alfalfa, carrots, and sunflowers, while others, such as beans, citrus, and lettuce, are considered Zn inefficient. Researchers are utilizing this variation to understand Zn efficiency and make improvements to crop yields. Crops like barley, potato, and sugar beet display medium Zn efficiency [25]. The ability to efficiently utilize Zn in soil can result in increased crop yields, even in soils with low Zn availability. Research has identified variations in Zn efficiency among different genotypes of crops, including rice, wheat, beans, maize, and others [26-27]. In recent years, the study of Zn efficiency in various crops such as wheat, beans, and rice has gained significant attention and research efforts have been invested in this field [28]. Extensive field studies have identified Zn-efficient wheat genotypes in low-Zn soil in several countries [29]. The common bean and rice are two crops that are particularly important in many regions across the world. While the common bean is known to be sensitive to soil Zn deficiency, research has shown that it is possible to identify Zn-efficient genotypes through screening experiments. Rice, on the other hand, is a staple food crop for over half of the world population and holds a yearly value of USD 3 billion in the United States, making it an economically significant crop as well [30]. Recent advancements in high-throughput phenotyping systems will provide opportunities for enhanced evaluation and forecast of the Zn efficiency of rice. Despite being grown in soil with low Zn content, rice displays a broad genetic diversity in terms of Zn efficiency [31]. The genotypic variation in Zn efficiency among maize cultivars has been observed in various regions around the world, including Brazil, where maize is a staple food crop and considered to be one of the most important cereal crops globally. The significant variation provides opportunities for crop breeding and selection efforts aimed at improving yields in low-Zn soil environments [30].

Studies have increasingly revealed the presence of natural genetic variations in plant's ability to absorb and utilize zinc (Zn). This opens up new avenues for exploiting these differences to enhance crop resilience to low Zn conditions [30.] Investigations in recent times have brought to light the specific genetic locations responsible for the efficient utilization of Zn in crops like rice, wheat, maize, and soybean. This discovery presents a positive opportunity to enhance crop Zn

Figure 2. A Venn diagram displays the plant species categorized as (a) zinc-deficient and (b) zinc-sufficient, with the overlapping area representing plant species that are only mildly efficient in obtaining zinc [32].

efficiency through innovative breeding techniques and the utilization of genetic engineering.

Strategies for Improving Zinc Efficiency in Crop Plants:

Zinc is a vital element for the growth and development of plants, and different species and varieties have evolved their own methods for acquiring the necessary Zn or making the most efficient use of it [33-35]. Crops and varieties that are proficient in utilizing Zinc (Zn) are capable of achieving sustainable growth and producing high yields, particularly in alkaline soil conditions. These Zn-efficient crops can play a significant role in resolving Zn deficiency challenges faced by farmers [36]. Despite the numerous studies conducted on Zn efficiency in food crops like wheat, beans, rice, and chickpeas, a comprehensive comprehension of the underlying mechanisms and natural genetic variations of Zn utilization still eludes us. In order to advance our understanding of zinc efficiency in crops, it is essential to gain a more in-depth understanding of the physiological and genetic factors that determine zinc efficiency [37]. The efficiency of Zn is a multifaceted characteristic that can be attributed to a combination of various mechanisms operating at different levels. This complexity makes it difficult to determine the precise reasons behind its efficiency [32]. There are several strategies for improving Zn efficiency in crop plants, including genetic improvement, nutrient management, and agronomic practices. In this section, we discuss the mechanisms of Zn efficiency in crops [38].

Candidate Mechanism 1 for Improving Plant Zinc Efficiency: Zinc Uptake Systems and Zinc Transporters:

Plants absorb Zinc (Zn) through various structures like the root epidermis, cortex, endodermis, pericycle, xylem, stem, leaves, phloem, and seeds. Over the last three decades, researchers have been striving to understand the science behind Zn efficiency in plants and to formulate efficient breeding approaches for crops that would optimize Zn utilization [39]. Although several Zn efficiency mechanisms have been proposed in literature, root uptake studies have provided the most evidence [40]. However, recent studies have shown that root Zn2+ influx is not strongly correlated with Zn efficiency, especially in wheat, suggesting that Zn efficiency may be more of a shoot-focused trait than a root-focused one [41].Soil type and pH play a crucial role in Zn availability to crops. Alkaline soils and sandy soils with low total Zn levels are prone to Zn deficiency [42]. Plants produce organic compounds known as Phyto siderophores, which can impact the accessibility of Zinc (Zn) to the plant. The process of Zn uptake by the roots is a complex phenomenon and occurs in two stages, which are characterized by high-affinity and low-affinity transport systems. The absorption of Zn into the roots is facilitated by several types of transporter proteins, including ZIP family, HMA family, MTP family, VIT family, and PCR proteins [43]. These transporter genes are regulated by transcription factors and may also be influenced by Phyto siderophores. "Conducting additional studies on the transporter proteins responsible for Zinc (Zn) uptake will greatly enhance our understanding of how crops can withstand low Zn soil conditions, which often hinder their growth and productivity [44]. The systems and transporters responsible for Zinc (Zn) uptake in plants play a pivotal role in determining the efficiency of Zn utilization in crops. Current research has pinpointed a number of genes and transporters involved in Zn uptake and transportation in different crop species [45]. These findings provide a promising avenue for improving Zn efficiency through genetic engineering and breeding approaches.

Candidate Mechanism 2 for Improving Plant Zinc Efficiency: Internal Utilization of Zinc in Shoots:

"Zinc (Zn) is a singular metal in that it contributes to the functioning of all classes of enzymes, including lyases, transferases, isomerases, oxidoreductases, and hydrolases. This wide-ranging involvement in enzymatic activities can have a significant effect on the overall efficiency of Zn utilization [46]. It has been reported that Zn deficiency can inhibit carbonic anhydrase in crops, and as such, it is needed for the proper functioning of over 300 enzymes [47]. To maintain crop yields, it is crucial to cultivate crops that are more efficient in their use of Zn [48]. Research suggests that Zn efficiency is related to a shoot-coordinated pathway, and that Zn-efficient crops use more effective internal utilization mechanisms than Zn-inefficient crops [49]. This is because Zn is an essential component of several key enzymes. Studies suggest that the utilization of Zinc (Zn) in the shoots of plants is dependent on Zn-requiring enzymes. Elevated activity of enzymes such as carbonic anhydrase and Cu/Zn superoxide dismutase in Zn-efficient wheat varieties has been linked to improved Zn utilization in these crops [50]. Research conducted on wheat has shown that the physiological utilization of Zinc (Zn) is a key determinant of Zn efficiency. The concentration of Zn in wheat grain has been linked to the activities of two important enzymes, superoxide dismutase and carbonic anhydrase [51]. To gain a more comprehensive understanding of Zinc (Zn) efficiency, it is crucial to continue research efforts aimed at discovering new genes associated with internal Zn utilization within the shoots of crop plants and exploring the connections between Zn efficiency and Zn-dependent enzymes in crops.

Internal Zn utilization in the shoot is also an important mechanism for improving Zn efficiency in crops. Studies have identified genetic loci and biochemical pathways involved in Zn utilization in the shoot [52]. These findings provide a promising avenue for improving Zn efficiency through genetic engineering and breeding approaches [53].

Additional Mechanisms:

Future research is needed to uncover additional mechanisms contributing to Zn efficiency in crops, such as root architecture or seed Zn levels [54]. The soil conditions and environmental factors of a location can affect the micronutrient levels, like Zn, in seeds [55]. Seed Zn content is important for human nutrition, and QTLs for seed Zn have been identified in crops like wheat, rice, maize, and beans, offering opportunities for breeding Zn-biofortified varieties. Studies have also found QTLs for Zn, Cu, and Cd concentrations in brown rice, as well as major QTLs for Zn efficiency and seed Zn accumulation in wheat and grain Zn and Fe QTLs in rice [56]. In order to enhance global crop tolerance to low-Zn soils, it is important to expand our knowledge of the physiological and molecular genetics aspects of Zn efficiency in plants. A deeper understanding of this will aid in developing better strategies for improving crop growth and yields in low-Zn soil environments [57].

In addition to Zn uptake and utilization, there are other mechanisms that contribute to Zn efficiency in crops, such as root morphology, metal tolerance, and phytohormones [58]. Further research is needed to fully understand the mechanisms involved in Zn efficiency in crops.

Final Thoughts, Upcoming Challenges, and Prospective Outlook:

The significance of zinc in human nutrition cannot be overstated, as it is a crucial element in ensuring a well-rounded and nutritious diet. Its role is essential for maintaining a healthy balance in our diet and overall well-being. A considerable amount of the zinc intake of humans comes from plants, which are a predominant source of nourishment. Understanding the role that zinc plays in the growth and function of plants is therefore vital to ensuring the continued health and well-being of the global population. The study of Zn-efficient crops that can withstand low Zn soil stress is contributing to our growing understanding of Zn's impact on living organisms. A thorough understanding of the strategies for maximizing zinc efficiency, the inner workings of plant cells, and the genes involved can lead to a more sustainable agriculture, enhanced human nutrition, and a decrease in the reliance on synthetic fertilizers. "Improving the productivity and nutritional value of crops through enhanced zinc efficiency can assist in meeting the food requirements of the rapidly expanding global population. In order to delve deeper into the topic of zinc efficiency, future studies should concentrate on the following aspects: (1) Establishing the genes and processes associated with zinc efficiency in plants; (2) Examining the capabilities of cutting-edge genome editing technology (CRISPR-Cas9); (3) Improving techniques for measuring zinc efficiency in food crops; (4) Examining the metabolic changes that crops undergo in response to low zinc conditions; and (5) Undertaking genome-wide association studies to gain insight into the genetic foundations of zinc efficiency and the buildup of seed zinc in low zinc conditions.

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