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Mitigating Zinc Deficiency in Plants and Soils through Agronomic Techniques: A Review

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Abstract: Zinc (Zn) deficiency occurs widely in plants and soils. The occurrence of Zn deficiency in soils is completely associated with high pH, low available Zn content, and high organic matter in the soil while in plants it is the combinations of chlorosis, rosetting, dieback, and depressed or abnormal vegetative growth. Due to Zn deficiency in plants, many diseases have been reported in humans such as it disturbs immune response and the endocrine system and induces and produced brain disorders. Deficiency of essential elements such as Zn can be mitigated by techniques such as food supplementation, food fortification, and bio-fortification. From these techniques, biofortification is an economical and appropriate technique as it proposed to overcome the micronutrients such as Zn deficiency by elevating their contents in edible field crops that are in the access of poor farmers. It improves the nutritious status of edible parts of cereals through genetic (conventional breeding, transgenic approaches) or agronomic (application of micronutrients via soil, seed and foliar techniques) ways. Up to now millions of households are receiving paybacks from diversified diets and consuming micronutrient-rich crops. In this review, the zinc biofortification of crops, through agronomic practices, crop breeding, and transgenic approaches are described briefly.

Keywords: Biofortification, fertilizer, hidden hunger, micronutrients, seed coating, seed priming,

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1. Introduction

United Nations Sustainable Development Goals (SDGs) are future development agendas to meet fundamentals requirements by following a sustainable future of the world through better human-nature relationships (Keitsch, 2018). Nutrition is the basic need of SDGs "End Hunger, Achieve Food Security and Improved Nutrition and Promote Sustainable Agriculture". The overall goal of SDGs is to promote healthy and sustainable diets and to overcome food security issues in the global community (Mensi and Udenigwe, 2021). In the aspect of good health and well-being, Zinc (Zn) contributes as essential nutrient for life, its deficiency can have serious consequences in living organisms, as it is required for proper growth and functioning. Around 17% of the global population is facing the risk of Zn deficiency (Romana et al., 2021).Zinc supplementation promotes health through human and crop nutrition, wound healing, sunscreen, and the energy source powering hearing aids. Zinc-enriched foods can help in reducing malnutrition (Hernández-Camacho et al., 2020; Wani et al., 2017).

Zinc is the essential micronutrient for the human body and its metabolism. It is used as a catalyst for

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more than 100 enzymes. Zinc helps in gene expression and works as a regulator for protein folding activity (Tsave et al., 2018). Afterward iron (Fe), Zn is the most important element in the human body and is disseminated richly as a trace element. Zinc plays a significant part in performing functions in many biological processes for the proper growth and reproduction of plants (Noman et al., 2019). Considering plant dry matter, Zn is present in 30-100 mg per kg^{-1} in plants. It has been reported and estimated a long time back that 49% of global and 71% of Pakistan's soils for crop cultivations are deficient in Zn (Imtiaz et al., 2010).

World Health Organization (WHO) reported that developing countries such as Pakistan have the most common mineral elements such as Zn, Fe, and vitamin-A deficiencies (WHO, 2015). Globally, about 2.77 billion people around the globe are under severe deficiency of zinc and this situation is more common in Asia and Africa (Karaköy et al., 2013). In Pakistan, more than 33% of children and 50% of mothers are victims of Zn deficiency (Akhtar et al., 2013). Malnutrition of Zn predominantly has more impacts on the health of women, children, and older people and it is reported by WHO that 17.65% community is affected by malnutrition. Developing countries from sub-Saharan African and South Asian regions are prevailing these malnutrition conditions and almost 29% of the population from these regions having reduced growth due to malnutrition (WHO, 2015).

Less dietary ingestion is also associated with Zn deficiency and almost 1 out of 3 people from the globe are affected by its insufficiency (Escobedo et al., 2019). Zinc deficiency causes adverse effects on human beings, especially at age of 1-12 years, such as disorders in the immune system, damages in physiological growth, less ability of learning, development of cancer, and impairments in DNA (Ho et al., 2003; Black et al., 2008). Greater than 4% of the overall mortality and morbidity in kids under 5 years and sixteen million of the worldwide disability-balanced life years are because of Zn deficiency (Black et al., 2008; Walker et al., 2009).

It is a substantial public-spirited challenge to increase Zn concentration in food and field crops. It is an important element for human health; even its small deficiency can cause a disaster. Loss of appetite, taste and smell failure, anorexia, and some of the other symptoms of Zn deficiency show its impacts on the immune system, anemia, and arteriosclerosis.

Among the malnutrition factors, Zn stands at the fifth number in most developing nations while it attained 11th number world widely. It has equal importance as vitamin A and Fe are the basic requirements of the human body. All over the world, Zn has its effects on almost more than two billion individuals or every third individual is suffering from Zn deficiency (FAO, 2015). Gao et al. (2006) reported that in paddy production deficiency of Zn occurs in both direct-seeded and flooded systems. In tropical rice, Zn deficiency is the most widespread disorder and occurs in Sri Lanka, Nepal, Bangladesh, Philippines, India, Japan, China, and the USA. Severe deficiency of Zn causes physiological disorders e.g. chlorosis, the crop grows at a slower rate and decreases tillering, and increases the spikelet sterility. Zinc deficiency shows its symptoms prominently at the early stages of growth and sometimes its recovery occurs at later stages of growth (Rehman et al., 2016).

It has been stated that zinc deficiency in rice is more prominent in lowland on flooded conditions and continuous flooding reduced the Zn accessibility for the growing crop (Alloway, 2009). Conventional cultivation of rice includes usage of Zn in nursery seedlings and also after transplanting with flooding water at different stages (Doberman and Fairherst, 2000; Naik and Das, 2007). According to estimation, 50% of the overall production of rice might be exaggerated by the insufficiency of Zn (Imtiaz et al., 2010; Nadeem et al., 2013).

2. Zinc Deficiency in Plants

Zinc deficiency affects the production of reactive oxygen species (ROS) and antioxidants (Burman et al., 2013), and also plant membranes are destroyed (Aravind and Prasad, 2004). This membrane perturbation also destroys the chloroplast (Jung et al., 2008). Net CO_2 assimilation is reduced by photosynthesis, which reduces carbohydrate metabolism (Sharma et al., 2003). The severity of Zn deficiency in physiological processes varies from plant to plant (Hajiboland and Amirazad, 2010).

The deficiency of Zn affects various aspects of plant growth including the growth of leaves, the biomass of shoots, and the complete development of the plant (Wissuwa et al., 2006). Hajiboland and Amirazad (2010) reported that the superoxide dismutase and carbonic anhydrase increase in conditions of Zn deficiency, affecting leaves rather than the roots and thus decreased the biomass of the leaves. Broadley et al. (2007) stated that plant growth is highly regulated by auxin, which reduces its synthesis in absence of Zn, which leads to a reduction in plant height due to reduced internode distance.

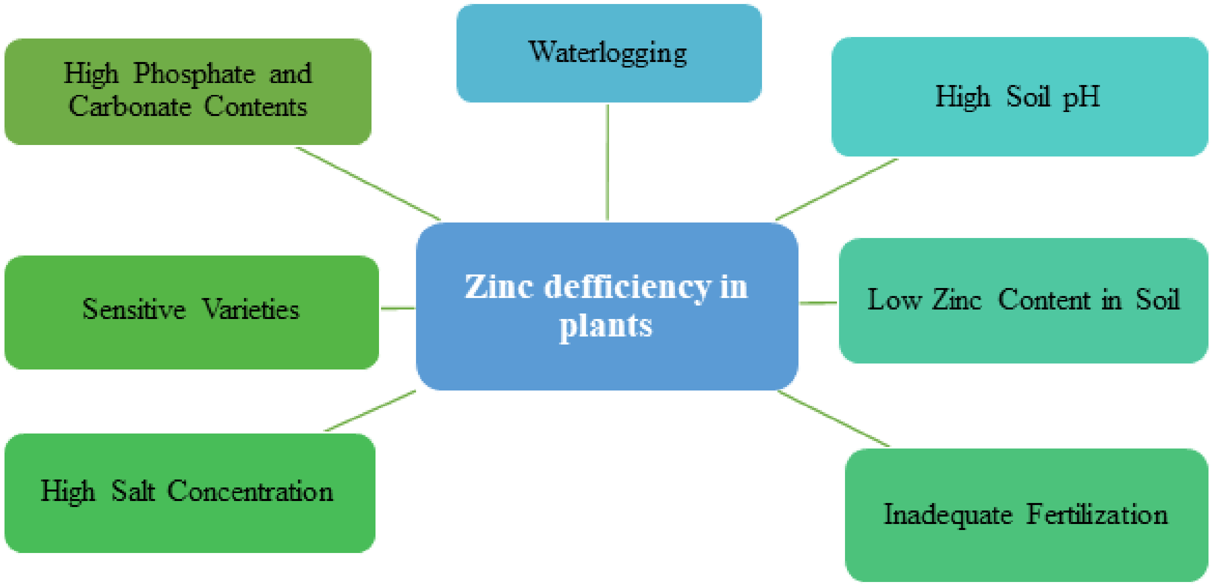

Fig 1. Factors affecting Zn deficiency

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3. Zinc Deficiency in Soil

The deficiency for Zn is very common in various areas of the globe especially in the wheat-rice cropping system of the sub-continent of Asia (Cakmak, 2008; Nawaz et al., 2015). More than 29% soil of the world is under the severe condition of Zn deficiency (Alloway, 2009). In Pakistan, alkaline soils have Zn as the maximum scarce micronutrient after nitrogen and phosphorus (Ullah et al., 2018). Cereals are more vulnerable to the insufficiency of Zn in contrast to legumes which lead to the decrease in grain yield and also its nutritional value (Cakmak et al., 1997). Rice crop is severely affected due to Zn deficiency as compared with other cereals and crops plants (Fageria et al., 2002).

Therefore, the insufficiency of Zn is studied as one of the vital nutrient strains that inhibit the yield of irrigated rice in Asia a present. Under low Zn availability plants will produce poor quality products with low yield (Welch and Graham, 1999). For example, a substantial reduction (80%) in kernel Zn absorption was detected in cereals when they grow on soils that have low availability of plant-available Zn (Cakmak, 2008). This reduction in Zn of grain is the cause of a decrease in its bioavailability in human beings and it may contribute to Zn shortage in susceptible human populations (Hussain et al., 2012). The problem of Zn deficiency is flattering one of the major health issues in public in various countries especially in countries where people depend on cereal-based food production (Cakmak, 2008).

Generally, Zn deficiency is considered higher in the calcareous soil, sandy soils, and peat soils, and in soils that have a higher rate of phosphorus, calcium carbonates, and silicon (Alloway, 2008). Salinity/Sodicity and calcareousness of soil from arid to the semi-arid condition in Pakistan is directly related to Zn deficiency (Ghafoor et al., 2001). Pakistani soils are mostly calcareous (Maqsood et al., 2016). It is reported that only a small portion of Zn is available to plants for their proper growth while it is present in relatively higher concentrations (Prasad et al., 2012). The plant-available forms of Zn in soils are free ions (Zn^{2+} and $ZnOH^{+}$), soluble organic complexes, and labile Zn (Shuman et al., 2001).

4. Zinc Deficiency Management

4.1. Biofortification

Biofortification is the procedure of enhancing the natural bioavailability of minerals in several crops (White and Broadley, 2005). Biofortification of rice with Zn can save between 1.6 to 2.3 million DALYs (Disability Adjusted Life Years) (Singh and Prasad,

2014) and 0.4-1.5 million DALYs (De Steur et al., 2012) every year in China and India, respectively.

Improving crop varieties by essential micro-nutrients is only possible through biofortification by adapting plant breeding or agronomic biofortification approaches and through modern techniques such as transgenic, biotechnology and fertilization strategies (Pfeiffer et al., 2007; Srivastava et al., 2015). Soil status and fertility remain unaffected through biofortification of crops, however, it is reported that in soil application some micronutrient contents were increased (Maqbool and Beshir, 2019). It is reported that kernel Zn concentration for rice can be increased with fertilizer Zn (Nadeem et al., 2013). Biofortification may be attained by two distinctive methods i.e. enhancing bioavailable micronutrients in the edible part of plants through

- Breeding or hereditary engineering i.e. genetic biofortification (Welch and Graham, 2004)
- Using different agricultural interventions (considerate fertilizer use) i.e. agronomic biofortification (Welch, 2002).

4.1.2. Genetic Biofortification

Genetic biofortification is an approach used in plants to accumulate maximum micronutrients (Zn and Fe) in cereal crops (Blair et al., 2013). These plants can reduce the contents of anti-nutrients and increase the contents of the constituent, thereby promoting the concentration of nutrients through breeding (Bouis, 2003). Breeding programs are aimed at developing new genotypes with high Zn concentrations for the survival of beneficial genetic variations of Zn storage in cereals (Prasad et al., 2014). Bio-fortification perceived via breeding is a tough approach to reach the Zn and Fe requirements. The plant breeding approach can be used to minimize the extent of Zn deficiency and is thought to be cost-effective, easily useable and affordable in the target populations. A breeding program with goals of the development of new genotypes having high Zn contents first requires the existence of useful genetic variation for Zn accumulation in grain. A very little information is available about the genetic control and molecular physiological mechanisms participating in the high accumulation of Zn and other micronutrients in the grain of different genetic materials of cereal crops (White and Broadley, 2011).

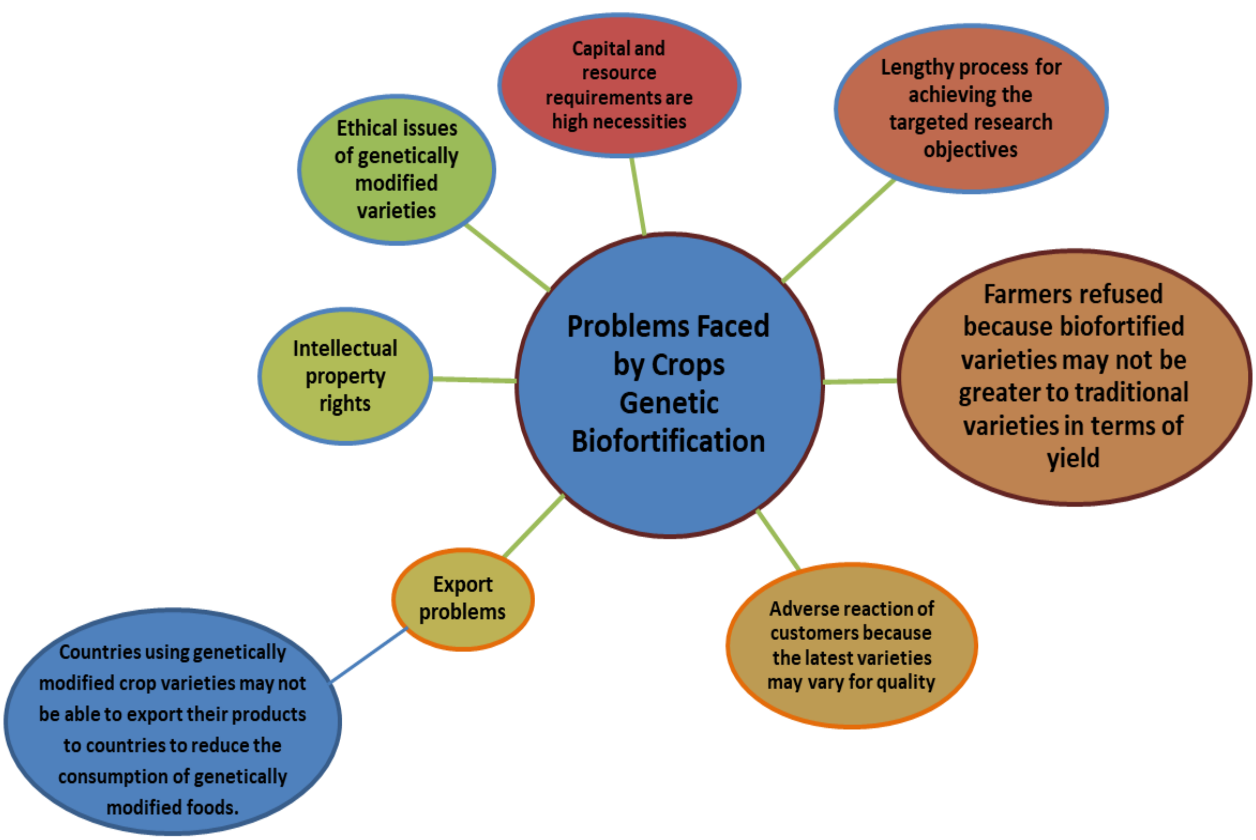

Fig. 2. Issues associated with crops genetic biofortification

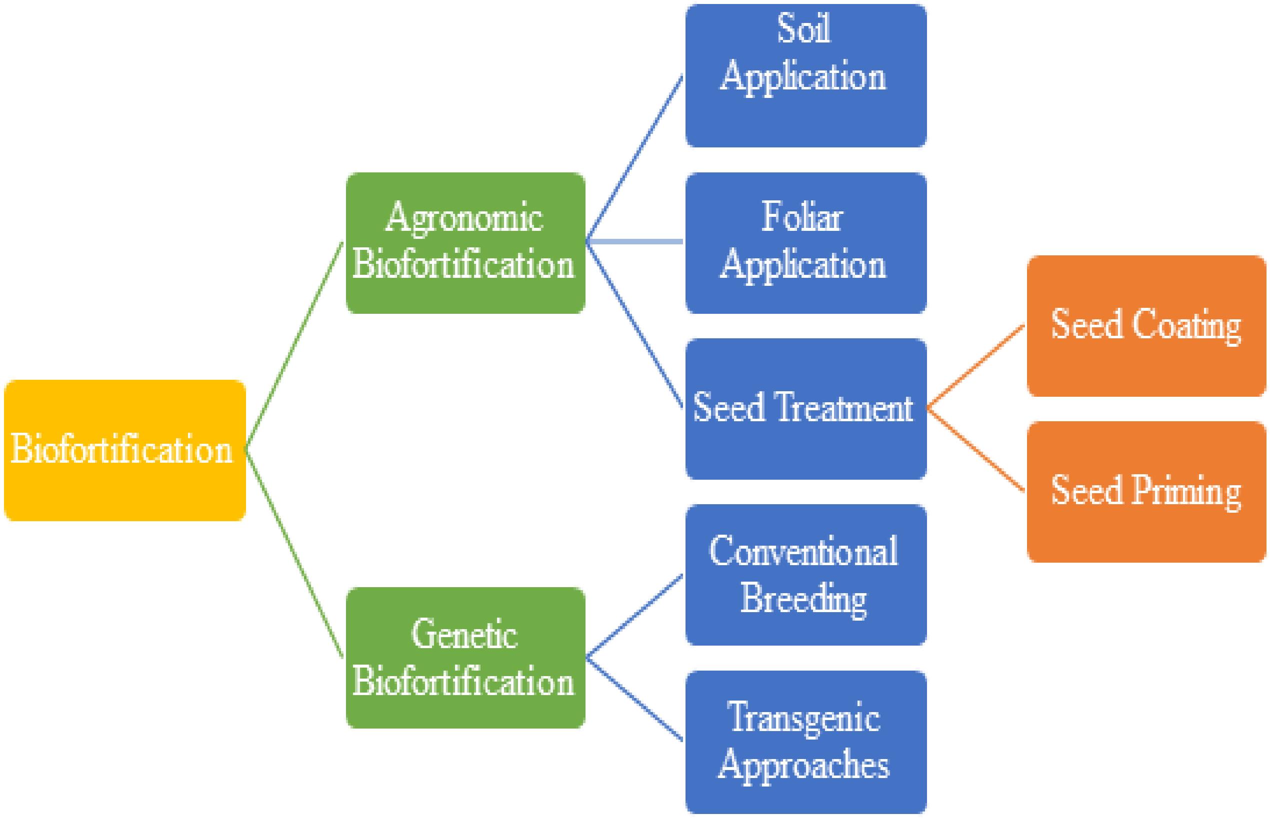

Fig 3. Biofortification techniques to mitigate nutrients deficiencies

4.1.2. Agronomic Biofortification

The approach that can be achieved in the short term is agronomic biofortification (Cakmak, 2008). It is also believed that the forthcoming strategy is to overcome micronutrient deficiencies in developing countries. Biofortified rice can be raised to overcome the needs of Zn and deliver an effective diet to replace conventional rice for this susceptible population (Chomba et al, 2015). Taking into account the above discussion, the plan will be used to study the consequences of Zn on the growth of plants and increase the Zn content of rice grains to overwhelmed Zn deficiency in humans (Ali et al, 2021b).

Strategies such as application of mineral fertilizers via the foliar method, soil application, and seed treatments are used for improving the soil nutritional properties, mobilization of mineral elements are the important characteristics of agronomic biofortification for field crops such as rice and micro-elements like Zn (White and Broadley, 2009). When we grow a crop in the soil where mineral elements are not available, the application of the soluble inorganic fertilizer to the roots or leaves is carried out in a targeted manner (Lambers et al., 2008). Selection of suitable micronutrient-intensive cultivars and crop rotations that upsurge the contents of Zn in the edible portion of plants.

In developing nations, agronomic biofortification is a win to win tactic (Welch and Graham, 2004), which relies on micronutrient-intensive cultivars (Sharma et al, 2010) for application of Zn fertilizer to seeds in seed treatment, soil in soil application, plant parts via foliar application method, higher than the optimum doses essential for maximum yield, to increase the absorption of Zn by plants and their movement into seeds (Hussain et al, 2012). This may be a more sustainable and cost-effective strategy to increase the concentration of Zn in rice (Singh, 2011). The application of soil microbes (Purakayastha and Chhonkar 2001) and the selection of appropriate crop rotations (Jat, 2010) have become very promising for increasing the concentration of Zn in rice grains.

4.2. Zinc Deficiency Management in Plants

Various techniques are used in different ways which have an impact on crop yield and Zn availability in the grain. Essential micronutrients can be applied to crop plants in many ways can be made available to plants through different techniques like priming, coating, foliar, and soil application.

4.2.1. Seed priming

Seed priming is a hydration method in which seeds are treated/soaked before sowing that permits seeds to achieve their pre-germination activities without radical *protuberance* (Nawaz et al., 2013). Uniform stand establishment has been observed in primed seeds as compared to dry seeds crop establishment. (Farooq et al., 2018). Nutri-primed seeds help to improve the crop growth, quality, and grain yield of both rice and wheat (Rehman et al., 2012).

With the increase in the concentration of $ZnSO_4$ a rise in the grain Zn concentration and yield in paddy were observed (Zulfiqar et al., 2021, Ali et al., 2021b). Seed Zn contents were increased in seed priming with nutrients (Zn) before sowing and resulted in healthier germination, even seedling and better crop stand (Harris et al., 2007). Another study indicated that seed priming with 0.05% Zn solution increased the grain Zn contents and grain yield by 19 and 29% (Harris et al., 2008).

4.2.2. Seed coating

Nutrients applied in fine powder form with the help of adhesive material such as arabic gum to apply on the outer surface of the seed is called seed coating. Seed coating affects the soil or seed at the soil-seed interface which may influence the availability of coated and soil-applied nutrients (Farooq et al., 2012). However, several factors including coated micronutrients, nutrient: seed ratio, soil moisture, soil type and fertility, material used for coating to alter the efficiency of micronutrients applied through seed coating (Halmer, 2008).

Zn seed coating also improved the yield of various field crops including rice and wheat (Rehman et al., 2016). Zinc seed coating in the wheat crop can help in improving the germination, seedling growth, Zn concentration in tissue than control (Slaton et al., 2001).

4.2.3. Foliar application method

Zinc foliar application has improved the Zn quality in rice, and advantage of that it has few rates of application as treatment and dodging Zn losses by soil fixation (Slamet-loedin et al., 2015; Nasri et al., 2011). Furthermore, Zn foliar usage increases Zn contents in brown rice than by soil application (Wissuwa et al., 2008).

Time of foliar application, types of various Zn fertilizers may have different effects on grain Zn content. Recently, several experiments have been studied on the time of Zn foliar application in cereal crops (Saltzman et al., 2013). It has been reported that foliar application of Zn after flowering (for example, in the early stage of milk plus dough) more significantly increases the Zn concentration of the grain (Phattarakul et al., 2012). Cakmak et al. (2010) reported that Zn foliar application can seriously affect Zn grain concentration.

Leaf Zn application significantly increased the Zn content in rice grains, and the application of Zn in soil did not have much effect on increasing grain Zn concentration. An experiment was conducted to estimate the effects of seed priming and foliar spray of Zn on hybrid rice, results showed that foliar application significantly increased plant height, ear length, cob diameter and 1000-grain weight, biomass yield, grain yield and harvest index as compared to seed priming (Barua and Saiki, 2018).

4.2.4. Zinc soil application

The application of Zn fertilizer in the soil is a general method for treating Zn deficiency (Cakmak and Kutman, 2018) and increasing Zn content in grains (Jiang et al., 2008), yet this technique isn't constantly ideal from a financial point of view (Prasad and Shivay, 2020) and may be familiar with breeding techniques (Cakmak, 2008). This requires the development of stabilization and increments of plant-based Zn uptake and use through a breeding plan. The application of Zn is carried out directly as organic and inorganic compounds. Due to its high solubility and cost-effectiveness, most applications of zinc sulfate ($ZnSO_4$) are used as inorganic sources of Zn. Zinc appliances can also be carried out in the form of EDTA zinc, zinc oxide (ZnO), and zinc oxysulfate.

The existence of large genotypic variation in Zn concentration (13.5-58.4 mg kg^{-1}) (Chang et al., 2005) and differential genotypic response to Zn deficiency also indicate the feasibility of conventional breeding for high-yield rice varieties and high grain Zn density in these rice production systems (Wissuwa et al., 2008, Ali et al., 2021a).

4. Conclusion

Recent research and developments in agriculture concluded that an increase in micro-nutrient contents in edible parts of staple field crops can be lessened during its cooking and processing. After ingestion by humans, the nutrient present in food remains bioavailable. Bio-fortification is the most appropriate, proven, and feasible option to combat malnutrition, particularly for those poor people in developing countries who live in remote areas. Fertilization of micronutrients, conventional breeding, and genetic engineering are tools of biofortification. To date, wheat, rice, maize, potato, beans, and pearl millet have been biofortified. To enhance the concentration of micronutrients in edible crops, the research focus should be on the integration of agronomic practices and genetic strategies to improve the transport of minerals to phloem-fed tissues and the identification of mechanisms influencing the homeostasis of minerals in plant cells.

Competing Interest Statement: All the authors declare that they have no competing interests

List of Abbreviations: Zinc, Zn DALYs, Disability-Adjusted Life Years; Fe, Iron; ROS, Reactive Oxygen Species; SDGs, Sustainable Development Goals; WHO, World Health Organization; Zinc: Zn.

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