Review Article

Agronomic Zn Biofortification of Cereal Crops a Sustainable Way to Ensuring Nutritional Security: A Review

Abstract

Nutritional deficits in humans and animals constitute a hidden epidemic in many impoverished areas across the world. The staple foods of developing South Asian and African nations, such as rice, wheat, and maize, are poor in micronutrients. In recent past, a lack of food diversification i.e., cereal-based crops low in minerals, is another danger to nutritional quality and security. Because of the inherently low-level accumulation of nutrients in cereal crops, they are the primary target for bio-fortification among all crops. Among different micronutrients, zinc (Zn) is an important micronutrient that plays a vital role in a variety of physiological functions, and its scarcity will result in lower crop yields and productivity. Agronomic practices like application of fertilizers in soil, nutri-priming, foliar spray etc. enhance the availability and uptake of Zn in crops. As a result, the growth and development, quality parameters and yield attributes of crop enhanced significantly. Therefore, agronomic biofortification of Zn in cereal crop is utmost important to achieve nutritional quality and food security. Furthermore, biofortification boosted the crop productivity to alleviate hidden hunger, in addition to quality aspects, proving to be a sustainable and cost-effective strategy. With soil and foliar fertiliser applications, including amendments, the agronomic interventions boost the Zn concentration in cereal crops. In this review the importance of agronomic Zn biofortification as a procedure to improve cereal yield and as an agricultural solution to solve nutritional quality and food security challenges is discussed.

Keywords: Agronomic interventions, Cereals, Foliar feeding, Malnutrition, Sustainable agriculture

1. Introduction

The ever-increasing population poses a global threat to the nutritional security. Nutrition security is defined as "one when all the people at all the time consume food of sufficient quantity and quality in terms of variety, diversity, nutrient content and safety to meet their dietary needs and food preferences for an active and healthy life, coupled with a sanitary environment, adequate health, education and care" (Anonymous, 2012). This issue is significantly more serious in low-income countries since farmers there use extensive agricultural approaches to boost productivity and profitability. Imbalance diets, a lack of variety in food sources, eating foods with lesser nutritional value, and food insecurity all have a negative impact on human health (Gundersen and Ziliak, 2015, Praharaj et al, 2021). Thus, nutritional security is utmost important for human being as well as animal. In the recent past years, the micronutrient deficiency become widespread across the world (Ernawati et al., 2021). Micronutrient deficiency is not only limited to developing countries but it also becoming prevalent where the staple food is cereals (Malik and Khan, 2021). The micronutrient insufficiency in soil restricting nutrient uptake in plants and, eventually, humans. Inadequate intake of these micronutrients has significant biological consequences because they play such an important role in the human body's functioning (Allai et al., 2022). For plants, 17 mineral elements are deemed important, whereas for humans, the number exceeds 22 (White and Broadley, 2005). Out of those nutrients, deficiency of essential micronutrients such as Fe and Zn affects more than 2 billion individuals around the world (Huang et al., 2020, Mandi et al., 2021, Prasad and Shivay, 2020). Globally, Zn deficient soils are much more widespread than that of other micronutrient deficiencies. Zn constitute about 3000 different proteins and various classes of enzymes (Malik and Khan, 2021). Low Zn uptake may pose a threat to 60–70% of the population in Asia and Sub-Saharan Africa (Praharaj et al., 2021). Zn deficiency causes lead in DNA damage, a weaker immune system, cancer, heart disease, issues during female germ cell pregnancy, and other issues in humans (Gibson, 2012, Hotz and Brown, 2004). Besides this, mostly in developing low-income Asian and African countries cereals are staple food, accounting 55% of the dietary energy (Anonymous, 2008). Due to their maximum consumption and availability per person (464.6 g person^{-1} day^{-1}) as well as their reactivity to micronutrient fertilisation, cereal grains are thought to have the most potential to serve as the finest carrier of micronutrients for relieving malnutrition (Shivay et al., 2008a, Mandi et al., 2021). Furthermore, wheat, rice, and maize are the three cereals that currently provide up to 60% of the daily energy intake of human populations (Tilman et al., 2002,). Low dietary intake, which is linked to a high consumption of cereal-based meals, is a common cause of zinc deficiency (Yaseen and Hussain, 2021). Cereal-based foods have very low Zn contents when compared to animal-based foods (Cakmak and Kutman, 2018). An adult's man daily Zn requirement is 9–18 mg day^{-1}, which cannot be met by cereal-based diet low in Zn content (Malik and Khan, 2021). When staple foods like wheat, rice, and maize are bio-fortified with zinc, it could significantly reduce nutritional insecurity because these foods are consumed by a huge number of people worldwide (Bouis and Welch, 2010, Shahane and Shivay, 2022, Wessells and Brown, 2012). Therefore, it is the need of the hour to increase the uptake and bioavailability of Zn in cereal crops to eradicate the nutritional security and improve the food quality. There are many options to improve nutritional security, including dietary diversification, food fortification, and medical supplementation. In fact, bio-fortification is a useful strategy for reducing malnutrition (De Valença et al., 2017, Saeid et al., 2019). Thus, to bridge the gap between nutrient supply and lower availability of Zn in the cereal grain, agronomic bio-fortification of Zn could be a novel approach to enhance the nutritional security.

2. Global status of Zn deficiency

In order to maintain better health, one must consume enough calories per day and a variety of foods to meet supplemental nutritional demands. Undernourishment is a major risk factor for death and other negative health effects, especially in children and mothers. In 2018, 9.2% of the world population were defined as severely food insecure. As a share of the population, food insecurity is highest in Sub-Saharan Africa where nearly one-third are defined as severely insecure (Anonymous, 2019). The highest prevalence of undernourishment was in Africa followed by Asia (Figure 1). Globally the status of Zn deficiency varies and it is shown in Figure 2. Country with highest population of Zn deficiency was found in Tazikistan (Figure 2). In high-income regions such as North America, Europe, Oceania, and Central Asia, Zn insufficiency affects less than 5–10% of the population, whereas it affects 15–50% of the population in Sub-Saharan Africa and South Asia, with the greatest prevalence of 54% in the Democratic Republic of Congo (Dhaliwal et al., 2022). Up to 453207 deaths (4.4% of childhood deaths) and 1.2% of disease burden (3.8% of children 6 months to 5 years) were attributed to Zn deficiency in

South America, Africa, and Asia. Furthermore, Africa, Asia, and Latin America were the regions with the greatest rates of zinc deficiency. 47% of all fatalities in India, Nigeria, the Democratic Republic of the Congo, Ethiopia, and Afghanistan were caused by zinc deficiency (Gupta et al., 2020). According to data on zinc intake, between 17.6% and 29.6% of people in South and Southeast Asia, Sub-Saharan Africa, and Central America were at danger of not getting enough zinc. The risk in South Asia and Sub-Saharan Africa was the greatest (>25%). Pregnancy difficulties, low birth weight, reduced immunological competence, mother and infant mortality and morbidity, and development failure in infancy and childhood may all be linked to zinc deficiency. Zn deficiency is also widespread in different types of soil. Its deficiency is mostly prevalent in sodic soil, saline soil, calcareous soil, paddy soil, sandy soil, and highly weathered soil (Prasad et al., 2016)). The Zn deficiency first detected in rice crop at Pantnagar, Uttarakhand in 1965 by Nene (1966). Currently, 48% of Indian soils are deficient in zinc, with that number anticipated to rise to 63% by 2025 (Singh, 2009). In India, about 10 mha area are affected by zinc deficiency, and about 85% of rice-wheat system cropping occurs in the Indo-Gangetic plain, which has calcareous soils with high pH and consequently limited Zn availability. Improving the production from this cereal belt is consequently critical for the country's grain production to maintain sustainability (Singh et al., 2005). Based on the foregoing, it has been theorized that human Zn deficiency is linked to soil Zn content and relative cereal intake in the diet. Thus, deficiency of Zn in the soil leads to human Zn deficiency and child stunting, globally and particularly in South Asia (Bevis et al., 2023).

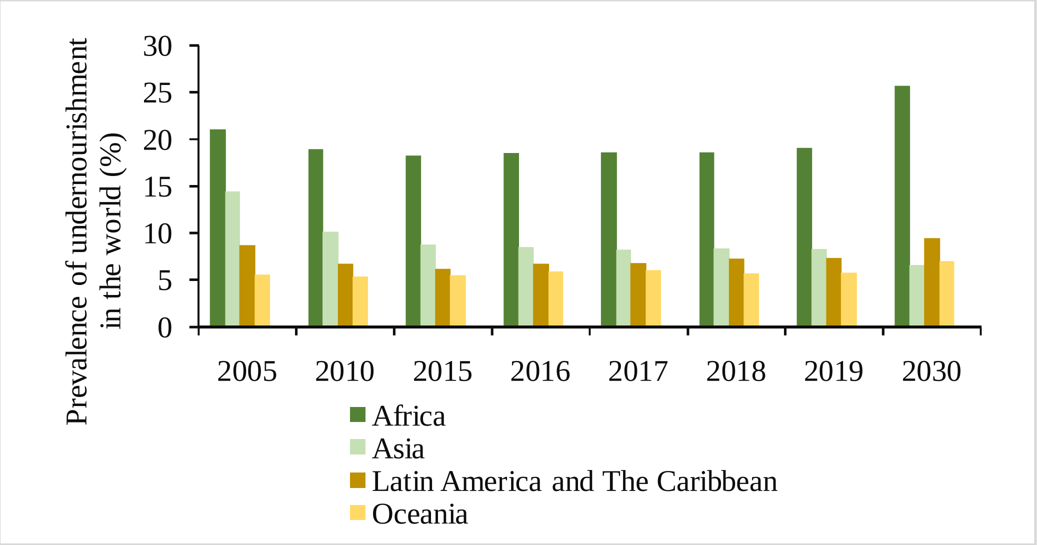

Figure 1: Prevalence of undernourishment in the world (Anonymous, 2020)

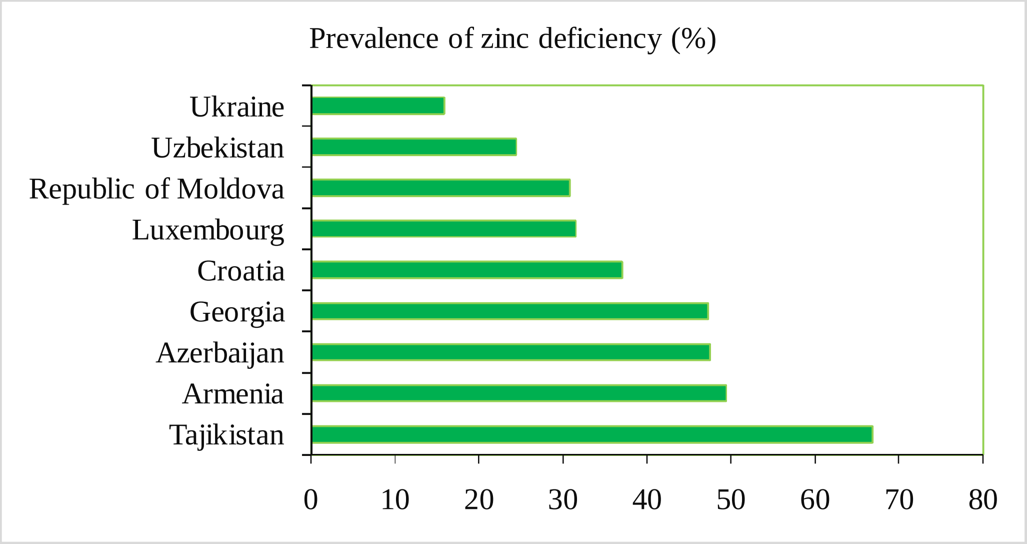

Figure 2: Countries with highest population of Zn deficiency (Anonymous, 2015)

3. Functions vis-à-vis deficiency symptoms of Zn in plant system

Zn plays a vital role in plant nutrition. Zn influence synthesis of protein, membrane integrity, phyto-enzyme activation, elimination of abiotic stress, enhanced quality of crops etc. in plants (Ganguly et al., 2022). It plays a role in carbohydrate metabolism. The enzyme involved is carbonic anhydrase. Zn helps in detoxification of superoxide radicle, the enzyme involved is copper zinc superoxide dismutase. It has a role in anaerobic root respiration in rice. The enzyme involved is ADH (alcohol dehydrogenase). Zn imparts resistance to disease in plants (Cakmak et al., 2018). Zn is required for the synthesis of tryptophan, which is a precursor to IAA, and it also plays a role in the creation of auxin, an important growth hormone (Alloway et al., 2008, Hafeez et al., 2013). The Zn is also necessary for maintaining the integrity of the cellular membrane in order to keep macromolecules and ion transport systems in their structural orientation. Its interaction with phospholipids and membrane proteins' sulphydryl groups aids in membrane preservation (Kabata-Pendias et al., 2004). Zn also aids nitrogen metabolism, chlorophyll production, protein synthesis, and photosynthesis, as well as providing resilience to stress. Zn also increases nitrogen metabolism, chlorophyll production, protein synthesis, and photosynthesis, as well as providing tolerance to stress (Hassan et al., 2021, Hassan et al., 2020). As Zn is relatively immobile in plant system, its deficiency symptoms generally appear on the growing young tissue. In rice, the characteristic symptom of Zn deficiency is bronzing. Zinc deficiency appear 2–3 weeks after rice seedlings are transplanted, with leaves developing brown blotches and streaks that may fuse to completely cover older leaves, and plants remaining stunted, whereas in severe cases, the plants may die, and those that recover will show significant delay in maturity and yield reduction (Prathap et al., 2022). Zn application also helps in mitigating drought stress, salinity stress, and heavy metal stress (Luo et al., 2012; Zhao etal., 2011). Because Zn is immobile in deficit, the deficiency symptoms show first on young leaves. The upper leaf surfaces acquire interveinal chlorosis and necrotic spots, which eventually unite to form brown necrotic and brittle patches (Vadlamudi et al., 2020). Interveinal chlorosis, or "mottle leaf," the appearance of a bronze tint or "bronzing," a reduction in leaf size or "little leaf," internode shortening or "rosetting," and root apex necrosis, or "dieback disease," are all symptoms of severe zinc deficiency. (Broadley et al., 2007).

4. Functions vis-à-vis deficiency symptoms of Zn in human physiology and health

Zn plays a pivotal role in biological system. Zn has several functions in human physiology i.e., reproduction system, nervous system, endocrine system, heart disease and hyper tension (Table 1). It is essential for the expression of genetic potential; nucleic acid synthesis, repair, and structural integrity all require Zn. It helps in different catalytic activity in the human body and it is essential for bioactivity of more than 300 coenzymes (Kanwar and Sharma, 2022; Zastrow and Pecoraro, 2014). Due to many catalytic activities in human body, Zn is an important prime mineral for working of immune system. The reason behind Zn deficiency includes poor absorption, alcoholism, improper diet intake etc.The human body has 2-3 g/kg of Zn of human body, with 60% of it found in muscle, roughly 30% in bones and 0.1% in blood plasmas. Zn is advised at 11 mg day^{-1} for adult men and 8 mg day^{-1} for adult women (Uwitonze et al., 2020). Zn is also engaged in membrane stabilisation and cellular protection by preventing lipid peroxidation and lowering free radical production. Poor Zn nutrition during pregnancy may cause low birth weight. Zn is such an essential element for human health that even a small shortage can be fatal. Loss of appetite, anorexia, loss of smell and taste, and other symptoms are caused by a lack of Zn in humans, and it can also impair the immune system, producing arteriosclerosis and anaemia (Gondal et al., 2021). Zn is essential for bone digestive system, and aids to increase the amount of vitamin D in bones (Younas et al., 2022). Skin issues, recurrent infections, and dwarfism are all common in toddlers and school-aged children (Prasad et al., 2014, Roohani et al., 2013). Zn also influences gene regulation, intra and inter cellular signalling, and stabilization of membrane. Furthermore, it helps in hormone production, secretion and sexual development (Malik and Khan, 2022). The important sources of Zn in human diet are marine foods such as crab, oysters, lobster, and other shellfish, red meat and poultry, dairy products such as cheese, legumes and nuts, whole grain cereals, and other sources (Prasad et al., 2016, Shahane et al., 2022). The amount of Zn absorbed from the food varies depending on a variety of dietary and physiological factors. Zn deficiency may also cause Alzheimer's and Parkinson's disease (Adani et al., 2020). In humans, a lack of Zn causes a variety of issues, including immune system dysfunction, skin difficulties, lower IQ levels, joint discomfort, memory loss, night blindness, anorexia, child mortality and sexual maturation issues (Maret and Sandstead, 2008; Younas et al., 2022).

Table 1: Function of Zn in human physiology

Human physiology	Role of Zn	References
1. Reproduction system	Control the growth, fertility, and pregnancy of female germ cell, ovarian function, antral follicular development.	Garner et al. (2021), Foresta et al. (2014), Vickram et al. (2021)
2. Nervous system	Required for normal brain development and function, Increased blood-brain barrier permeability, inhibits antagonist binding to muscarinic acetylcholine receptors,	Takeda (2001), Frederickson et al. (2001)
3. Endocrine system	Thyroid hormones, androgens, and notably growth hormones metabolism, Zinc enhances circulation levels of IGF-I and potentiates IGF-I membrane signalling and intracellular	MacDonald (2000), Salgueiro et al. (2002), Baltaci et al. (2019)

	second messengers that drive cell proliferation by influencing growth hormone synthesis and secretion as well as hepatic IGF-I synthesis.	
4. Diabetes mellitus	Involved in insulin secretion, storage, metabolism, and signaling.	Taylor (2005), Dunn (2005)
5. Heart disease and hypertension	Helps to defend against the oxidative stress that causes atherosclerosis in endothelial cells and reduce arterial hypertension.	Tubek (2007)

5. Factors affecting Zn deficiency in plant system

Zinc deficiency can be seen in almost every country, and almost all crops react well to Zn application (Welch, 2002). Because over half of India's soils are deficient in accessible Zn, Zn shortage has gotten a lot of attention. There has been great emphasis on Zn fertilization in cereal crops in north-western India. Zn deficiency is occurred in almost all type of soil: submerged soil, sandy soil, loamy soil, soils formed from basalt, granite, leached soil etc. Zn deficiency is more prominent in calcareous and alkaline soil (Norouzi et al., 2014). The factors mostly affecting the availability of Zn are pH, calcium carbonate content, parent material, organic matter, soil moisture, soil temperature, plant species and genotype. The parent material one of the most important factors that influences Zn availability and determines Zn concentration in soils. The amount of Zn in soil is determined by the weathering of the rocks from which it is made (Rashid and Ryan, 2008, Wang and Busbey, 2005). The solubility of Zn is highly pH dependent and decrease 100 folds with each unit increase in soil pH. Zn deficiency is mostly occurred in alkaline soil rather than acid soil (Alloway et al., 2008). Because soil Zn solubility is lower in alkaline soils, the availability of Zn is lowered. Adequate soil moisture is utmost important in Zn uptake by plant. Lack of soil moisture results in Zn deficiency in soil. In arid and semiarid region Zn deficiency occurs due to high calcium carbonate and low organic matter content (Imran et al., 2014). The most prominently Zn deficiency was observed in aerobic rice system (Prasad, 2011). Flooded soils are more commonly related with zinc deficiency than dry soils. Rice plants, for example, suffer from Zn shortage in calcareous soil when submerged. The interaction of zinc with free sulphide caused zinc shortage owing to floods. Because finer texture soils, such as clay, have higher CEC values, they have more reactive sites and can hold more Zn than lighter textured soils. Zn interacts positively with primary nutrient N and K as well as negatively with P (Prasad et al., 2016a). Zn reacts antagonistically with all the secondary nutrients. High concentration of Ca and Mg reduces the absorption and translocation of Zn in plant system (Prasad, 2011). Zn deficiency is also caused by high-yielding varieties, imbalance use of fertilizer, and heavy reliance on single-source fertilisers etc.

6. Factors affecting Zn deficiency in human

Zn deficiency in the human body is caused due to reduce bio-availability of Zn, insufficient Zn absorption by human body, consumption of food with low Zn content (Hussain et al, 2022). Most chemicals reduce Zn availability by forming an unabsorbable combination with soluble Zn in the intestinal lumen. Phytic acid (my-inositol hexa-phosphate), found in most cereal grains and seed legumes, is perhaps the most effective inhibitor of Zn absorption (Foster et al., 2012). In addition, a number of other substances, including copper, iron, and calcium, are known as Zn absorption inhibitors because they can decrease the intake of zinc in body (Cousins et al., 2010).

7. Response of cereal crops to Zn fertilization

Zinc (Zn) deficiency in cereal crops has become a major issue, resulting in lower yield and nutritional quality of the grain, harming human health. Agronomic management of cereal crops with Zn fertiliser has been reported as a promising method for improving seedling germination and production, as well as grain Zn concentration in cereal crops (NemeñoA, 2010, Phattarakul et al., 2016). Several parameters, including fertiliser supply, application timing and method, and soil chemical characteristics, have been reported to influence the efficacy of Zn fertiliser application (Wang et al., 2014). The adequate Zn fertilization application can help in increasing cereal production. Different response of Zn fertilization in cereal crops are presented in the Table 2.

8. Critical level of Zn in plant tissues

One of the main constraints to global food production is zinc deficiency. Identification of Zn-deficient areas and the various causes of shortage is therefore critical. According to Dobermann and Fairhurst (2000), the critical limits of Zn deficiency in plants are: 10 mg kg^{-1} definite deficiency, 10–15 mg kg^{-1} very likely, 15–20 mg kg^{-1} likely, and >20 mg kg^{-1} unlikely (sufficient). Zn sufficiency ranges from 15 to 50 ppm in the dry matter of mature plants in most crop species, with 15 ppm Zn regarded crucial in most cases.

9. Major approaches to achieve nutritional security

Three important strategies to achieving nutritional security are medical supplementation, dietary diversification and biofortification are presented in figure 3. (Dhaliwal et al., 2022). The first strategy, dietary diversity is a qualitative measure of food consumption that represents household access to a diverse range of foods and serves as a proxy for an individual's nutrient sufficiency. This strategy is involved in shift from monotonous staple starchy food crop to fruits, vegetable, pulses and animal diet which are rich in nutrition (Dhaliwal et al., 2022). Furthermore, this strategy is suitable in regions where people have a wide variety of foods; nevertheless, it is not relevant in all areas like developing countries where the majority of people are depend on starchy staple food (Bouis and Welch, 2010). Nutrient supplementation meaning supply of nutrients which are not available in sufficient quantity in daily foods. Nutrient supplementation is done by vitamins, amino acid, minerals etc. When there is Zn deficiency, Zn supplementation can be done. Furthermore, this approach is commonly recommended during acute Zn shortage, particularly during pregnancy and early childhood (Hussain et al, 2022; Stein et al., 2007). However, Zn supplementation is quite expensive and is only recommended when a quick response is required (Stein et al., 2007; Cakmak and Kutman., 2018). In underdeveloped countries, majority of people have not access to Zn supplementation. Biofortification is the process of increasing the micronutrient content in edible sections of a target crop without losing agronomic features such as pest resistance, yield, or drought resilience (Klikocka and Marks, 2018, Dhaliwal et al., 2022). Bio-fortification has the potential to solve the problem of micronutrient insufficiency (Bouis and Welch, 2010). Furthermore, it significantly increased crop yield in Zn deficient situations, and this method is thought to be a long-term solution to Zn insufficiency (Bouis and Welch, 2010). Different approaches of bio-fortification i.e., agronomic bio-fortification, genetic bio-fortification and genome engineering are presented in the figure 4.

Table 2: Response of Zn fertilization in cereal crops

Crops	Treatment	Increase in Zn concentration	References
1. Rice	Zn at 60 kg ha^{-1}	Increased grain Zn content was 0.5 mg plant^{-1} (29.1%) when Zn fertilizer was applied	Tuiwong et al. (2021)
	4.0% ZnCU+0.2% ZnFS ($ZnSO_4 \cdot 7H_2O$)	enhanced the grain Zn concentration by 54.5% over control and 2.3–2.5 times higher Zn concentration was observed in grain as compared to straw.	Bana et al. (2021)
	Zn at 10 kg ha^{-1}	When Zn was applied to wheat grain, it resulted in the highest level of Zn uptake (115.4 g ha^{-1}).	Lakshmi et al. (2021)
	3.5% Zn (ZnO- enriched urea)	Zn concentration in aromatic rice increased by 16.4 mg kg^{-1} grain.	Shivay et al. (2008b)
	1% urea+0.5% $ZnSO_4$ (N+Zn+)	Grain Zn concentration was the highest under foliar application of N+Zn+, with a 37.9% increase compared with control.	Tuiwong et al. (2022)
2. Wheat	8 mg Zn kg^{-1} soil	Increased grain Zn concentration of Zincol-2016 and Faisalabad-2008 by respectively 32 and 18% in industrial-zone soil, and by 15 and 2% in peri-urban soil.	Qaswar et al. (2017)
	Foliar application of 4 kg ZnSO4·7H2O ha^{-1}, and soil application of 50 kg ZnSO4·7H2O ha^{-1}	Improved the grain Zn concentration of wheat by 28% and 89% during the first and second growing seasons, respectively.	Wang et al. (2014)
3. Maize	ZnO nanoparticles	Maximum increase in grain Zn concentration (82%)	Umar et al. (2021)
	Zinc oxide nanoparticles (ZnONPs 20 mg L^{-1})	Increase the Zn concentration 4.167 mg kg^{-1} in shoot.	Tondey et al. (2021)

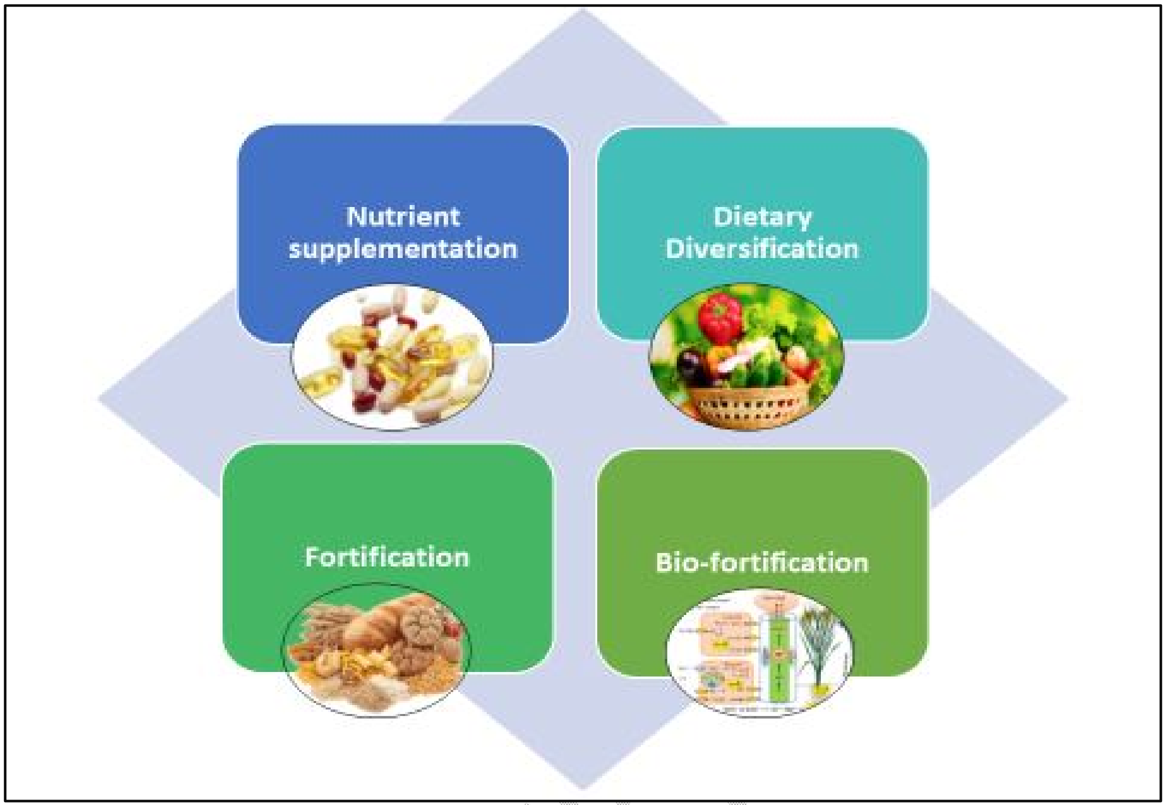

Figure 3: Approaches to achieve nutritional security

10. Agronomic interventions for Zn biofortification

Agronomic biofortification is the deliberate application of mineral fertilisers to raise the proportion of a specific mineral in consumable crop parts in order to enhance dietary intake of the mineral (Prasad and Shivay, 2020, Shahane and Shivay, 2022). Agronomic biofortification is not a competitor to genetic biofortification. Different types of agronomic interventions involved in biofortification are soil application of fertilizers, foliar spaying of fertilizer, nanoparticle fertilizers, phyto-siderophores and EDTA chelated Zn, nutrient priming etc (Figure 4). The majority of management approaches are aimed at increasing soil quality, which improves micronutrient availability for plant uptake and consequently food concentration. The plant's nutrient usage efficacy is determined by a variety of elements including soil physical, chemical, and biological features. Agronomic biofortification is a quickest and cost-effective tool to improve the aforesaid characteristics. The application of fertilisers significantly enhanced grain Zn content, and it could be a quick solution to the problem of Zn insufficiency. Additionally, this method also boosts Zn availability and crop yield grain yield and Zn content in the grain (Yadav et al., 2011).

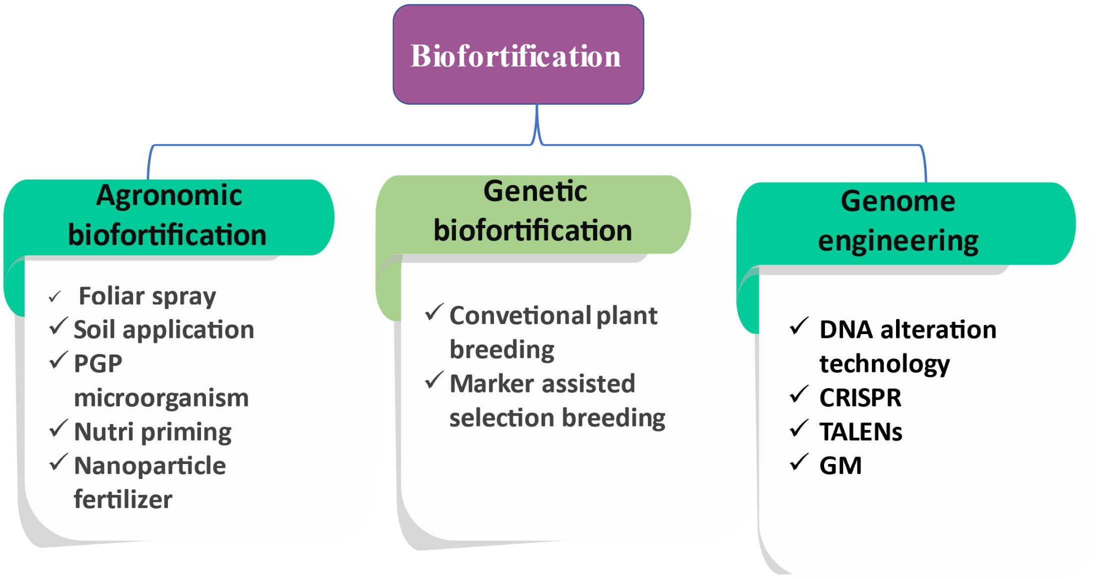

Figure 4: Different approaches of biofortification

10.1. Agronomic Zn biofortification via soil application of Zn

Micronutrient delivery through soil is the most adaptable and successful method due to its numerous advantages (Dhaliwal and Manchanda, 2009, Dhaliwal et al., 2012). Despite the fact that Zn deficit reduces crop productivity and grain Zn content, Zn deficiency can be addressed with Zn application. When substantial amounts of nutrients are required, the best technique for supplying them is by soil application. The treatment of high Zn is usually suggested for crops that are particularly vulnerable to Zn deficiency (Hassan et al., 2021). However, because of the reduced FUE, this approach necessitates a larger fertiliser treatment (Singh et al., 2005). Soil application of $ZnSO_4.7H_2O$ (21% Zn) at 62.5 kg ha^{-1} or $ZnSO_4.H_2O$ (33% Zn) at 40 kg ha^{-1} alleviate Zn deficiency in several crops (Ram et al., 2015).

10.2. Agronomic Zn biofortification via foliar feeding of Zn

Foliar micronutrient feeding increases grain Zn by reducing nutrient loss and allowing nutrients to be directly absorbed by plants (Hassan et al., 2021, Johnson et al., 2005). Zn sprayed foliarly increases grain Zn and bioavailability. Foliar-applied Zn is phloem-mobile and can easily be translocated into cereal grains during development (Haslett et al., 2001, Erenoglu et al., 2011). The time of foliar Zn fertiliser application determines its biofortification efficiency. Foliar Zn applications, in both wheat and rice, are more successful at enriching the grain with Zn if applied later rather than early in the growth process, preferably during grain filling (Boonchuay et al., 2013, Prasad et al., 2013). The fertiliser method for agronomic biofortification of wheat with zinc increases Zn concentrations in the endosperm, which is important for target groups who consume high amounts of white flour (Kutman et al., 2011). Even though a little amount of Zn is used in foliar feeding compared to soil applied Zn, foliar feeding is more effective in increasing the Zn content in grain and flour than soil application. The most essential and effective strategy for addressing Zn deficiency in cereals is foliar feeding. Furthermore, because of the increase in direct Zn absorption in arid and semi-arid locations, foliar application is considered a unique application strategy (Chapagain and Wiesman, 2004).

10.3. Agronomic Zn biofortification via Seed priming

Seed priming is the regulated hydration of seeds to allow them to complete their pre-germination metabolic activities without causing radical emergence (Lutts et al., 2016). This promotes many physiological processes in plants to combat the damaging effects of abiotic stressors while also increasing the nutritional value and production of crops (Wojtyla et al., 2016, Kranner and Colville, 2011, Sundaria et al., 2018). Seed priming not only reduces the time it takes for seedlings to emerge, but it also allows for more uniform germination and a higher germination rate. Primed seeds have a greater potential for uniform stand establishment and yield than dry seeds (Farooq et al., 2006). The seed priming with Zn fertilisers improved wheat productivity and Zn uptake by seeds substantially (Farooq et al., 2012). Wheat seeds can be efficiently treated with ZnO NPs to improve Zn nutrition (Elhaj Baddar and Unrine., 2018). Seed priming with Zn is cost-effective, environmentally benign, and produces a large boost in yield; nonetheless, SP has occasionally proven to be a non-beneficial approach.

11. Agronomic Zn biofortification via nanotechnology

Nano-fertilizers are typically utilized for the controlled release of nutrients into the soil, which can improve the availability of nutrients to various plant organs, resulting in higher production and quality (Khan et al., 2021, Sekhon, 2014). Nano-fertilizers are much more beneficial of plant development and environmental safety than a comparable amount of traditional fertiliser due to their capacity to cover a larger surface area and their efficient absorption by plants. These are used in smaller amounts, resulting in less leaching and less gas emissions into the atmosphere (Manjunatha et al., 2016, Adisa et al., 2019). The effects of nano ZnO differ depending on the plant species, growth stage, application type and duration, and doses used. Zinc oxide NPs had a potential advantage over ZnSO4 since they were less harmful to wheat crops at high concentrations, while also improving grain yield and Zn concentration (Du et al., 2019). Zinc hydroxide nitrate ($Zn_5 (OH)_8(NO_3)2H_2O$) has recently been investigated for use as a foliar spray. During the first growth stage, the novel source influenced Zn accumulation in maize stems and leaves, followed by its remobilization from the stems to other plant organs during the second development stage (Dhaliwal et al., 2022, Ivanov et al., 2019). The influence of weathered nano ZnO on grain Zn content was detected, weathered nano Zn showed 186 % increase in grain Zn content, whereas fresh nano ZnO showed a 229% increase (Dimkpa et al., 2020). Different bio-fortified cereal crops and their characteristics are discussed in the Table 3

Table 3: Biofortified cereal crops and their characteristics

Sl. no.	Crop	Biofortified varieties	Characteristics
1.	Rice	CR Dhan 310 (Protein rich)	Contains 10.3% protein in polished grain as compared to 7.0–8.0% in popular varieties

		DRR Dhan 45 (Zn rich)	High in zinc content (22.6 ppm) in polished grains in comparison to 12.0–16.0 ppm in popular varieties.
2.	Wheat	WB 02 (Fe and Zn rich)	Rich in zinc (42.0 ppm) and iron (40.0 ppm) in comparison to 32.0 ppm zinc and 28.0–32.0 ppm iron in popular varieties.
		HPBW 01 (Fe and Zn)	high iron (40.0 ppm) and zinc (40.6 ppm).
3.	Maize	Pusa Vivek QPM9 Improved	High provitamin-A (8.15 ppm), lysine (2.67%) and tryptophan (0.74%).
		Pusa HM4 Improved	0.91% tryptophan and 3.62% lysine rich.
		Pusa HM8 Improved	tryptophan (1.06%) and lysine (4.18%) rich
		Pusa HM9 Improved	0.68% tryptophan and 2.97% lysine rich.
4.	Pearl millet	HHB 299	High iron (73.0 ppm) and zinc (41.0 ppm).
		AHB 1200	Rich in iron (73.0 ppm).

12. Agronomic biofortification in the light of cost effectiveness

Agronomic bio-fortification is widely used in various parts of the world, and this method has a major impact on grain Zn content. The agronomic fertilisation technique is a quick and cost-effective way to address the Zn deficiency (Bouis and Welch, 2010). Foliar feeding is a cost-effective strategy, however, due to the need to spray multiple times during the growth season, it can become uneconomical. Agronomic Zn biofortication is the most efficient and cost-effective approach to boost mineral and molecule content in food crops (Prasad and Shivay, 2020). Biofortification reduces the burden of micronutrient deficiencies, according to several research (De Steur et al., 2011). It also has to figure out how much the biofortification process costs in order to accomplish these burden reductions. Initial expenses for basic breeding and research to develop micronutrient-enriched biofortified lines are followed by marginal costs for testing, adaptive breeding, maintenance breeding, dissemination, and extension efforts in crop biofortification. According to a World Bank report from 1997, public health interventions that cost less than USD 150 DALY^{-1} (Disability-Adjusted Life Years) saved are extremely cost-effective. Zn-enriched beans, rice, and wheat found that the bulk of the costs per DALY saved for biofortification fell into the extremely cost-effective category (Meenakshi et al., 2010).

13. Agronomic biofortification in the light of nutritional security and alleviating malnutrition

In comparison to non-biofortified crops, biofortified crops are nutritionally rich, assuming equivalent micronutrient bioavailability (La Frano et al., 2014). Because biofortified staple crops improve overall micronutrient intake and retention during cooking, processing, and storage. Nano-Zn particles improve the grain nutrient content in plants, making them a primary source of human health and easing malnutrition, their availability and level of accumulation should be closely regulated, as excessive intake can pose health hazards (El-Ramady et al., 2021, Rizwan et al., 2021). Many studies have shown that eating zinc-biofortified wheat starch boosts overall zinc absorption by 30–70% (Signorell et al., 2019, Lowe et al., 2020). As “Ending hunger, achieving food security and improving nutrition, and promoting sustainable agriculture” are the UN's second sustainable development goals, which can be achieved through Zn biofortification of cereal crop. The use of biofortified cultivars has a lot of potential for improving human health and well-being. Several studies have shown that these biofortified crops have beneficial impacts on people (Yadava et al., 2018). The development and promotion of biofortified varieties thus would be helpful in addressing malnutrition and achieving the SDGs (Paroda et al., 2019). In keeping with the Sustainable Development Goals set, it is paramount that agronomically Zn biofortified cereal crops be developed and provided to the rural poor to alleviate malnutrition.

14. Conclusion

In developing and undeveloped countries, the great reliance of the human population on cereal-based diets is the primary source of micronutrient insufficiency. To overcome micronutrient insufficiency in the human population, agronomic biofortification by fertilisation appears to be a viable and cost-effective solution. Breeding techniques for bio-fortification might be a lengthy, costly, and resource-intensive process. Conversely, agronomic bio-fortification of cereal crops is a promising strategy that has significantly increased grain yield and grain Zn levels to fulfil human demands.

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