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An Unravelled Potential of Foliar Application of Micro and Beneficial Nutrients in Cereals for Ensuring Food and Nutritional Security

Check for updates

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Abstract: Micronutrient deficiency in soil and crops is a critical issue that contributes to what is known as hidden hunger. Hidden hunger refers to the lack of essential vitamins and minerals in people diets, often due to the poor nutrient content of staple crops, which can lead to significant health problems despite adequate caloric intake. Micronutrients are required in small amounts but are crucial for various physiological functions in plants, including cereals for enzyme activation, photosynthesis, nitrogen fixation, and synthesis of vital compounds. Corrective measures to address micronutrient deficiencies include soil application, seed treatment, foliar sprays, and genetic biofortification. Foliar sprays are particularly effective as they allow for the direct application of nutrients to plant leaves, ensuring quick absorption and utilization. This method can rapidly correct deficiencies, improve crop yields, and enhance the nutritional quality of the produce. Previous research has shown the efficacy of foliar sprays in addressing micronutrient deficiencies. Additionally, advancements in nanotechnology have led to the development of more efficient foliar spray formulations that enhance nutrient uptake and minimize environmental impact. Overall, addressing micronutrient deficiencies through foliar sprays and other agronomic practices is vital for improving crop health, yield, and nutritional quality, thereby contributing to food security and the alleviation of hidden hunger. However, specific dose of each micro- and beneficial nutrients are highly related to crops and cropping systems, season, agroclimatic conditions, materials used, and crop growth stage. The review article focuses on all issues and concerns with possible options for correcting micronutrient deficiency in cereals to ensure food and nutritional security and agricultural sustainability.

Introduction

The Green Revolution (GR) was a pivotal initiative in agriculture in India that boomed in the 1960s and changed the food production scenario of the country (Patel, 2013; Gulati and Juneja, 2022; John and Babu, 2021). Improved varieties of staple cereals such as rice and wheat coupled with inputs supply-driven agronomic technologies were key drivers behind the success of self-sufficiency in food needs (Eseroghene and Ikechukwu, 2018; Das et al., 2021; Ghosh et al., 2021; Grote et al., 2021; Čech et al., 2022; Srikantha et al., 2023; Venipriyadharshini and Kavitha, 2023). However,

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the essential inputs, namely agrochemicals and water, were used non-judiciously (Sairam et al., 2020; Mishra et al., 2021; Banerjee et al., 2021). The over-exploitation of surface irrigation water and groundwater created a depletion of water resources, salinity, water and soil pollution by heavy metals (Bhattacharya, 2015; Bhattacharya et al., 2016; Samal et al., 2017; Chakraborty et al., 2019; Li et al., 2021; Roy et al., 2022; Mondal et al., 2022; Saha et al., 2022; Khondoker et al., 2023). The excessive use of chemical fertilizers and plant protection chemicals resulted in land degradation and pollution of water bodies.

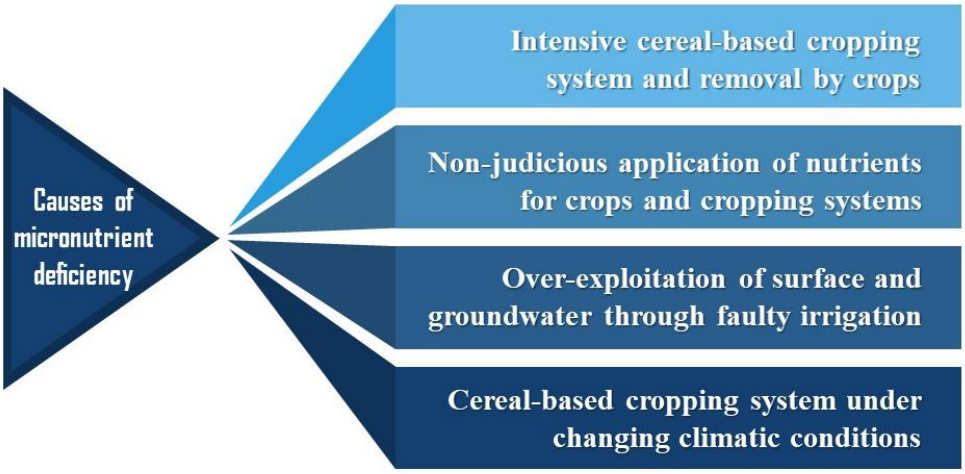

Figure 1. Causes of faulty agricultural practices for micronutrient deficiency system.

Further, unthoughtful use of chemical pesticides not only brought pesticide resurgence and residual toxicity in agricultural produce, causing harm to users but also reduced the population of natural enemies and poor ecosystem services (Sarkar et al., 2016; Maitra and Ray, 2019; Ray, 2019; Rajmohan et al., 2020; Maitra et al., 2021; Rad et al., 2022). The high-yielding and improved varieties of major cereals created genetic erosion of crops and reduced diversification (Liu et al., 2021; Albahri et al., 2023; Sagar et al., 2023a). Heavy machinery and excess tillage created problems like erosion of topsoil and nutrients (Bhattacharyya et al., 2015; Feeney et al., 2023). Undoubtedly, the GR was an important decision at that time to feed the hungry nation; however, proactive steps should have been taken to combat its ill effects. Over time, the negative impacts, such as yield plateauing and dwindling natural resources, become issues. Faulty agricultural practices have introduced micronutrient deficiency to the soil (Figure 1).

The GR technologies promoted chemical fertilizers for high-yielding genotypes, and the focus was more concentrated on the application of primary nutrients, namely, nitrogen, phosphorus and potassium. However, the application of secondary and micronutrients was neglected, and this has emerged as a significant problem over decades. Plants utilize all required nutrients for their flourish and optimum productivity, whereas the supply of only primary nutrients occasioned deficiency of other nutrients (Baldantoni et a*l*., 2019; Chrysargyris et al., 2022). Micronutrients play a critical function in plant growth and development. Still, they also play a decisive part in plant innate immunity and stress tolerance due to their contribution to metabolic pathways that regulate plants' defense systems and perceive stressors (Jan et al., 2022). Even with the established advantages of micronutrients, overuse of these nutrients can result in harmful environmental consequences, plant toxicity, soil contamination and adverse health effects (Rehman et al., 2019; Madhu et al., 2022).

Furthermore, given that micronutrients derived from plants are critical to human health, biofortifying crop end products with micronutrients is another crucial component of crop nutrition that could aid in the fight against mineral deficiencies that afflict a significant portion of the global inhabitants (Di Gioia et al., 2022). Even at deficient concentrations, mineral elements that exhibit growth-promoting properties and beneficial impacts are categorized as helpful elements. For some plant species, they are either completely unnecessary or only required under specific circumstances. They are sometimes referred to as potential micro-nutrients. Certain nutrients were found to influence the absorption, translocation, and use of other necessary elements, assisting the formation of vital metabolites and lessening the adverse effects of certain other elements or anti-metabolites through activating an enzymatic system or activity. Examples of such elements include sodium (Na), aluminium (Al), cobalt (Co), selenium (Se), iodine (I), gallium (Ga), vanadium (Va), and silicon (Si).

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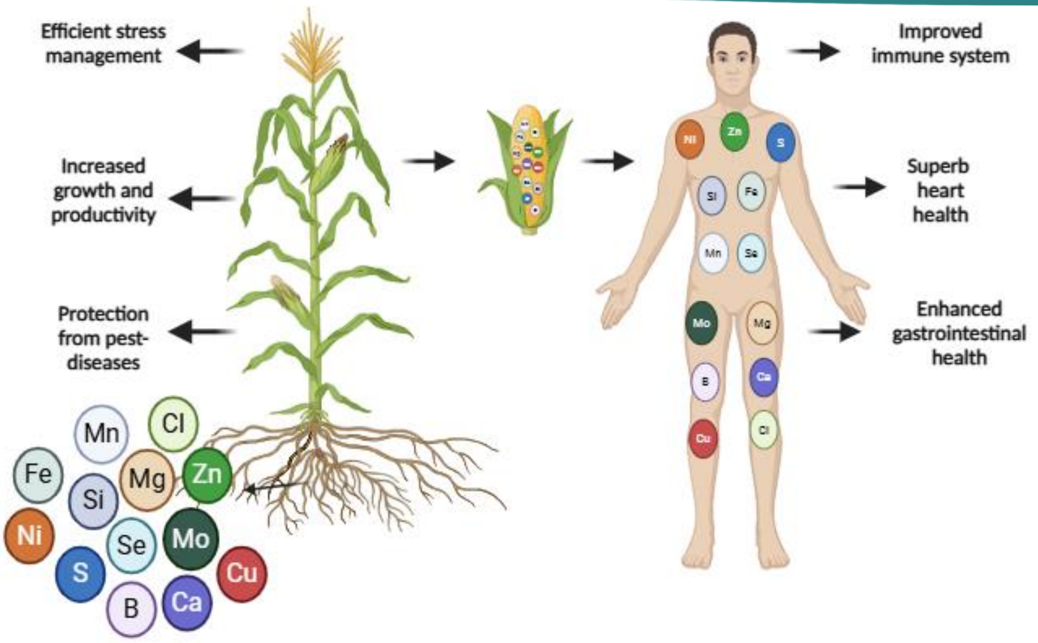

Figure 2. Healthy plants and human beings with appropriate nutrition.

The nutrients mentioned above perform vital roles in plants and show multifaceted activities in human bodies. During the post-GR era, people's diets became cereals-based, raising nutritional concerns. The insufficiency of micronutrients has affected about two billion people globally, negatively impacting health and economic well-being. Cereals comprise a noteworthy portion of the diet in developing nations in Africa and Asia with low incomes, for about 70-80% of total calorie intake (Laskowski et al., 2019; OECD/FAO, 2022). Cereals contain more calories but contain low fibre, minerals, antioxidants, and vitamins, which can harm adults' and children's physical and mental health (FAO, 2001; Rawat et al., 2023). The micronutrient deficiency in cereal grains is sometimes pronounced as hidden hunger. Cereal grains consist of four distinct components: the bran, endosperm, germ, and aleurone layer. The bran, aleurone layer, and germ contain a higher level of proteins and amino acids, vitamins, minerals, fibers, lipids and bioactive substances. The endosperm is rich in starch and reserve proteins, namely, prolamins and glutelin (Lopez-Gonzalez, 2019; Bartłomiej et al., 2012). The majority of whole grains are high in dietary fiber and bioactive substances. A high-fiber diet lowers the risk of atherosclerotic cardiovascular illnesses and cardiovascular death, ischemic stroke (Bechthold et al., 2017), type 2 diabetes (Aune et al., 2016; McRae, 2017; Sur et al., 2023; Biswas et al., 2023; Roy et al., 2023; Acharya et al., 2023) and obesity (Seal and Brownlee, 2015; Madhu and Sarkar, 2016; Sarkar et al., 2021, 2022). Therefore, it is the need of hour for the correction of micronutrients deficiency to combat with the hidden hunger.

Role of micronutrients in human body

Micronutrient deficiencies in the human body are common, and more than two billion people worldwide agonize (WHO, 2006; Harding et al., 2017). The second Sustainable Development Goal (SDG 2) encouraged the elimination of hunger as well as malnutrition at the time by endorsing food security (UN, 2024; Olson et al., 2021; Gil et al., 2018). Nevertheless, combatting the ever-increasing human population and the current threat of climate change results in insufficient production of food, creating a perplexed dimension to reach the goal (Ville et al., 2019; Sagar et al., 2023b). Plants and humans suffer from micronutrient deficiency and appropriate nutrition can provide a healthy individual (Figure 2). A typical example of micronutrient deficiency is zinc. Zn not only acts as a cofactor for more than 300 enzymatic reactions but also for the structural integrity of proteins, gene expression, physiological processes, defence and immune system, cell division, DNA synthesis, wound healing, and immune system performance (King and Keen 1999). It also encourages healthy growth and development, particularly during pregnancy and childhood, and aids in the healing of wounds. It is required for the reproductive system to operate properly, including the creation of sperm (Rink and Gabriel, 2000). Iron is an essential element for hemoglobin and forms part of myoglobin. Fe prevents and treats iron deficiency anaemia and supports overall energy metabolism and the production of neurotransmitters (Abbaspour et al., 2014). As a cofactor

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for antioxidants and enzymes, Se is a crucial trace element that aids in defending cells against damage brought on by free radicals plays a vital part in the appropriate operation of the immune system in the human body and promotes the synthesis of thyroid hormones and thyroid function (Hossain et al., 2021; Moulick et al., 2024). Although the study is ongoing, it might have a function in preventing certain chronic diseases. An important electrolyte that aids in blood pressure regulation and fluid balance maintenance is Na. It has a role in both muscle contraction and nerve transmission. It is maintaining healthy blood pressure and hydration levels in the human body. Although hyponatremia, or sodium deficiency, is rare, it can happen because of significant fluid loss (diarrhea, vomiting), which can cause symptoms including nausea, convulsions and, in extreme cases, coma and goiter (Dharmarajan et al., 2021; Farag et al., 2023). Si is a trace element that is used for the health of connective tissues, such as bones, cartilage, and skin. It also plays a part in mineralising bones and synthesising collagen, helping against osteoporosis, and maintaining the skin's suppleness and vitality (Carlisle, 1988; Pritchard and Nielsen, 2024). B is a mineral that affects various physiological processes, such as the metabolism of calcium, magnesium, and vitamin D. It keeps bones healthy and affects cognitive function and memory (Devirian and Volpe, 2003; Khaliq et al., 2018).

Fortified food supplements are generally provided to humans to recover from micronutrient deficiency; however, biofortified foods are safe (Ofori et al., 2022). In the biofortification process, genetic, transgenic and agronomic approaches are adopted. Genetic and transgenic biofortification refers to the development of nutrient-enriched genotypes through plant breeding and biotechnological tools (Medina-Lozano et al., 2022; Naik et al., 2024); however, agronomic biofortification is the procedure of application of target elements in the plant system, either in soil and plants as the crop is fortified biologically by uptake of desired nutrients (Bhardwaj et al., 2022). In the present consequences of intensive farming and the overexploitation of natural resources by adopting GR technologies, there is an urgent need to maintain soil health and cultivate agricultural sustainability (Maitra et al., 2023a,b). The present direction of agriculture should move towards crop diversification and cultivation of nutrients crops (Maitra et al., 2022a,b; Mukesh et al., 2024), conservation of resources (Sairam et al., 2023a), nutrients optimization (Sairam et al., 2023b) and adoption of appropriate cropping system (Maitra et al., 2000, 2023c; Gitari et al., 2020).

Further, the current context warrants an urgent need to correct micronutrient deficiency. This review article highlights the physiological and metabolic roles of micronutrients and beneficial elements in plants and their deficiency symptoms. Among agronomic biofortification methods, foliar spray of nutrients is well-thought-out as a suitable choice rather than applying them in soil, seed priming, and seedling root dipping. The article focuses on the foliar application of micronutrients as the simplest method of biofortification for combatting hidden hunger.

Role of micro and beneficial nutrients in plants and their deficiency symptoms

Micronutrients play multifaceted roles in plant growth and development. Some micronutrients are integral parts of various enzymes and secondary metabolites, which perform distinct functions in crop growth, productivity, and quality. Further, they facilitate plants' combat against various abiotic and biotic stresses (Figure 3). The important roles of micronutrients have been described below.

Zinc

Zinc, a divalent cation (Zn++), does not experience valence shifts, resulting in no redox activity in plants. Zn uptake is declined by high quantities of other divalent cations, such as Ca^{++} (Porcheron et al., 2013; Lee, 2018). Zn is a component of many enzymes. It is a structural, operational, or supervisory cofactor in numerous enzyme systems-reports of over 80 proteins containing Zn (Cobot et al., 2019). Zn-deficient plants show lower protein content and a slower rate of protein synthesis. Zn is essential for protein synthesis and building amides and amino acids. Ribosomes comprise Zn, which is necessary for maintaining their structural integrity (Ozturk et al., 2023). Increased RNA degradation rates also influence the reduction in protein content in Zn-deficient plants. Higher RNAse activity rates are a common sign of Zn insufficiency (Puzanowska-Tarasiewicz et al., 2009). Plants cultivated in calcareous and severely worn acid soils sometimes suffer from Zn shortage (Nazif et al., 2015). In the latter instance, low Zn levels are frequently linked to low iron levels.

The primary cause is Zn's limited availability in calcareous soils with high pH levels in which Zn is adsorbed to clay or $CaCO_3$. Moreover, elevated bicarbonate (HCO_3^-) concentrations significantly impede Zn absorption and translocation to the shoot. Indications of a zinc shortage in plants include reduction in internode length and stem length, terminal leaf rosetting, decreased

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production of fruit buds, mottled leaves, and interveinal chlorosis; anthocyanins can occasionally induce a red, spotty tint on the leaves. Phosphorus toxicity may result in chlorosis and necrosis symptoms in aged leaves of Zn-lacking plants (Marschner, 1993). *Khaira* is a prevalent symptom in rice, and it is caused by Zn deficiency (Sharma et al., 2013). Zinc cannot be absorbed by plants when their roots are constricted. Excessive pH levels can cause the zinc to become locked, preventing access to it.

Nutrient salts can be removed from the growing medium by flushing it with pH-neutral water, enhancing zinc absorption and restoring the proper amounts. Most plants prefer a soil pH between 6.0 and 7.0. Plants in the lower ranges more readily absorb Zn. Plants cultivated in hydroponic systems should have a pH between 5.5 and 6.0. Because of the improved absorption rate, the pH level should be maintained as close to 5.5 as feasible if the deficit is severe. Applying zinc topically to plants is a useful way to address zinc deficiency. To facilitate the plant's rapid absorption and usage of Zn, a solution of micronutrients is sprayed onto the leaves. This technique proves exceptionally beneficial in cases where the soil composition restricts the accessibility of zinc to plant roots. They experience no fixation since the foliar spray does not contact the soil (Praharaj et al., 2021). Studies have shown that directly treating zinc in crops such as cabbage and rice can significantly enhance nutrient uptake, yield and biofortification (Yogi et al., 2023; Açık

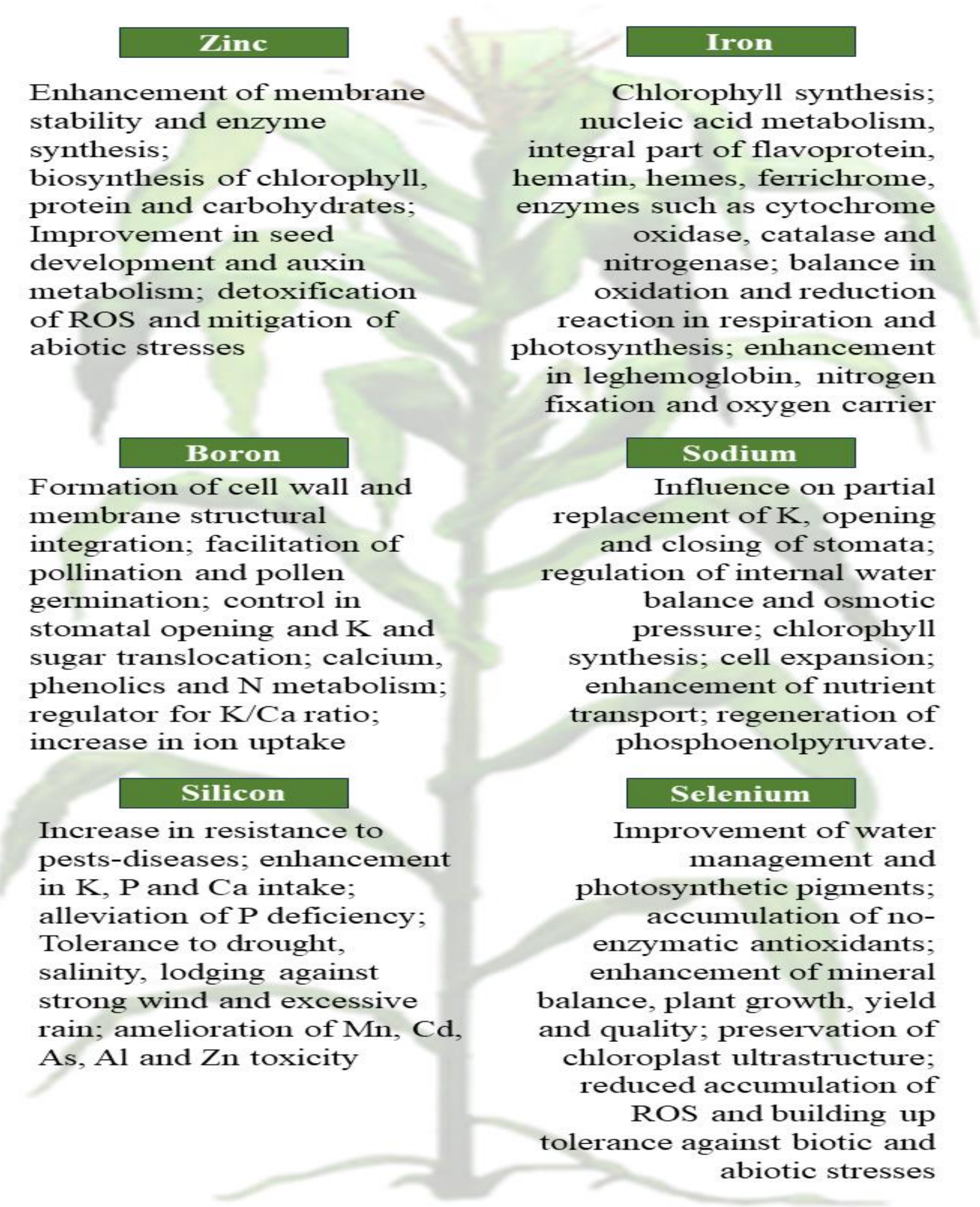

Figure 3. Important function of selective nutrients in plants.

Sümer, 2023). In addition, topical application of zinc increases zinc content in rice and improves crop yield and nutrient content.

Iron

Iron (Fe) in plant cells is essential for chlorophyll synthesis, and high levels of manganese or lime in soil can also cause iron deficiency in associations that stimulate various physiological developments such as photosynthate production, respiration, and N fixation (Rout and Sahoo, 2015). Plants absorb iron in the form of iron (Fe^{2+}) or iron (Fe^{3+}) ions (Brown, 1978). The ability of a metal to move rapidly between its two oxidation states in solution is essential for plant activity. Ferritin, a protein that encases ferric iron, is vital for plants to store iron. Iron is primarily insoluble in soil under aerobic conditions when it forms oxides and hydroxides. Ferric iron is frequently bound to organic chelates. As a result, in many soils, the concentration of free iron in the soil solution becomes very low (Mengel et al., 2001). Plants can mobilize iron and make it available for uptake by their roots. Iron absorption has two specific mechanisms. The first one, found in dicots and non-graminaceous monocots, lowers the pH of the rhizosphere by releasing protons. An inducible enzyme called Fe^{3+} reductase reduces ferric iron to ferrous iron at the plasma membrane. Then, a Fe^{2+}-specific ion transport system moves the reduced iron across the membrane. The second mechanism, found in corn, barley and oats, secretes siderophores (iron carriers) from the roots. These siderophores bind to ferric iron without reducing it (Cain and Smith, 2021).

Young leaves with interveinal chlorosis are signs of iron insufficiency (Li et al., 2021). Veins do not turn brown unless there is severe dieback or the death of entire plants or limbs. Iron deficiency symptoms are most noticeable on the newest and youngest leaves. In severe cases, the youngest leaves may be completely white and stunted, but there is usually no apparent physical defect. There are several ways of correcting iron deficiency, such as maintaining the soil pH, applying iron fertilizer to the soil and applying iron as foliar fertilizer (Layman et al., 2018). Applying fertilizer to the leaves is a valuable way to give them extra iron if they are iron deficient. Ferrous sulfate is a cheap and often used substance for this application ($FeSO_4.2H_2O$). Stir one gallon of water with one to two ounces of ferrous sulfate. It is possible to substitute an equivalent amount of chelated iron. However, foliar treatment yields few benefits from the more costly chelated forms of iron. Additionally, foliar sprays containing iron chelates, such as Fe EDTA and Fe EDDHA, can be applied to plants to give them instant access to iron (Ning et al., 2023; Zhang et al., 2022).

Boron

Boron plays a role in plant development by differentiating meristem cells. It is widely accepted that its primary function relates to the cell wall structure and associated substances (Fleischer et al., 1998). B content in plant tissues varies greatly, with dicotyledons generally having higher values than monocotyledons. In soil solutions with a pH below 8, boron mainly exists as boric acid ($B(OH)_3$), which is the main form absorbed by roots (González-Fontes, 2019). Boric acid only dissociates to $B(OH)_4$ at higher pH levels. B deficiency is a common nutritional problem (Blazier and Hennessey, 2008). B is easily leached from soils such as $B(OH)_3$ under high rainfall conditions. Increasing soil pH reduces the amount of available boron (Steiner and Lana, 2013), particularly in calcareous and high-clay soils. Drastic circumstances also induce a significant loss in availability, most likely due to boric acid polymerization and decreased B mobility via mass flow to the roots (Marschner, 2012). Plant shoots are impacted by a lack of B, particularly the terminal buds or youngest leaves (Zhang et al., 2010). They may become discolored or die. The internodes become short, making plants look bushy or rosette-like. The youngest plant tissues most likely show deficiency (Hong et al., 2009). Mature leaves may develop interveinal chlorosis or misshapen leaf blades. Boron deficiency also causes buds, flowers, and fruits to drop. Without enough boron, cells can divide but not differentiate properly. Boron also helps to regulate the use carbohydrates in plants (Ahmad et al., 2009). Boron does not move within plants, so it needs a constant supply at all growth points. Since B is immobile in plants, unlike nitrogen (N), its deficiencies initially manifested in the apical meristem of shoots and fruits. In soil with an adequate amount of B, deficiencies may arise from over-liming, wet or dry soil conditions, and low partial pressure of oxygen in the soil (Wójcik et al., 2008). According to Loomis and Durst (1992**)** and Mousavi and Raiesi (2022), Boron is essential to generative processes that impact pollen germination, pollen tube expansion, and other developmental processes. Thus, B deprivation is associated with the abortion of a flower and a poor fruit or seed set in B-sensitive plants (Mozafar, 1993). Usually, it is too late to provide B when B-deficient symptoms show up. Plants vary in susceptibility to B shortage, and B should be administered at rates suited to the plant when signs of B insufficiency arise. Since B is immobile in plants, plants growing in soils with poor B levels may experience a shortage throughout their peak

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growth periods. Therefore, a steady supply of B is needed throughout the growing season for optimum development and productivity (Mousavi and Raiesi, 2022). Another effective way to provide B to plants is through foliar treatment, especially in situations where root activity is limited and crop deficiencies in B occur in dry soil during the growth season (Ahmad et al., 2012).

Sodium

In plants, sodium (Na^+) has two different functions; under some circumstances, it can be a helpful nutrient, while under others, it may be hazardous. Although most plants do not consider sodium a necessary element, it can be helpful, especially when potassium (K^+) is lacking. For this reason, sodium is referred to as a functional nutrient. Na helps C4 plants with their metabolism (Maathuis, 2013). More specifically, it helps with the production of chlorophyll and the regeneration of phosphoenolpyruvate, which is involved in the manufacture of numerous aromatic compounds and carbon fixation (Subbarao et al., 2003). In plants, the mechanism of action of sodium involves multiple critical processes like Na^+ influx where nonselective cation channels (NSCCs), which permit the passage of many cations, including Na^+, are the primary route by which sodium enters plant roots followed by compartmentalization where Na^+ is divided into vacuoles by Na^+/H^+ exchangers after entering the plant (Keisham and Mukherjee, 2018). This sequestration into vacuoles lessens possible toxicity and lowers the cytosolic concentration of Na^{+6} and in the last efflux where Na^+/H^+ antiporters, including the salt overly sensitive 1 (SOS1) protein, can also remove sodium from plant cells (Giri and Varma, 2019). This process promotes Na^+ efflux from the roots of plants and aids in the maintenance of ion homeostasis (Keisham and Mukherjee, 2018).

In contrast, too high Na^+ concentrations in the environment, sometimes brought on by soil salinisation, can be harmful and force plants to deal with too much sodium in their tissues (Balasubramaniam et al., 2023). Over time, plants have developed ways to combat the adverse effects of high salt levels, such as effectively managing gene expression and transportation processes to regulate the levels of Na^+ in their cells. While specific mechanisms for monitoring Na^+ levels in plants are still unknown, broad processes for sensing the onset of salt stress have been described (Keisham and Mukherjee, 2018). In plants, sodium plays a variety of roles. It can be a helpful nutrient in some circumstances, while it can be harmful in others. Plants regulate their sodium levels through a complex system of absorption, compartmentalization, and efflux, as well as the capacity to detect and react to variations in the sodium levels in their surroundings (Zhao et al., 2021; Balasubramaniam et al., 2023). Chlorophyll production, turgor pressure, osmotic potential, cell expansion, lowering critical K levels, stomatal functions, nutrient transfer, enzyme activation, and growth stimulation are among the metabolic roles of sodium in plants (Nieves-Cordones et al., 2016). Unlike other critical minerals like nitrogen, potassium, or magnesium, the absence of sodium in plants does not cause any distinctive morphological changes or deficiency symptoms. Certain plants respond well to fertilization with sodium when they lack potassium (Thorne and Maathuis, 2022). To prevent toxicity, nevertheless, this should be done with caution.

Silicon

Silicon (Si) is a profuse element in the earth's crust. Its agricultural value continues to grow as its usefulness for crops becomes better known (Haynes, 2017). Although not considered an essential nutrient for all plants, silicon is pivotal in plant growth and crop production. It improves the plants' overall nutritional status and strengthens them against environmental challenges (Etesami and Jeong, 2018). By depositing silica in cell walls, silica reinforces the structural integrity and density of plants, making this reservoir indispensable to their growth and contributing to plant height by increasing the settlement resistance of the plant (Currie and Perry, 2007). Studies have shown that silicone reduces stress caused by salt, drought and heavy metals. It maintains ion homeostasis, regulates nutrient requirements, and provides biomass and growth (Mir et al., 2022). Promoting synthesizing organic materials and enzymes that aid plants in fending off fungi and insects, such as chitinase, peroxidase, polyphenol oxidases, and flavonoid phytoalexins. It can boost disease and pest resistance (Bakhat et al., 2018). It can also enhance photosynthesis efficiency by maintaining chloroplast structure and improving light absorption (Rastogi et al., 2021). The mechanism of action of Si starts with uptake as silicic acid, as plants can only extract silicon from the soil in this form. The ability of a plant to actively uptake silicon depends on its genetic makeup. Followed by two major transporters, Lsi1 and Lsi2, which are involved in the influx and efflux of silicon in rice and some other species. These transporters regulate silicon uptake from the soil, its distribution within the plant, and end deposition in tissues. After being taken up, Si is transported to various tissues, where it forms biogenic silica, which provides structural support and enhances the plant's defence mechanisms (Mitani-Ueno et al., 2023). Although silicon has been demonstrated to positively

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impact plant growth, robustness, quality, and stress resistance, it is not considered a necessary nutrient for many plants. Despite being uncommon given the quantity of silicon in the earth's crust, silicon deficits can nevertheless happen, particularly in soils that are heavily worn and leached or have low fertility (Schaller et al., 2021). New leaves, roots, or stems that are deficient in silicon often exhibit distortions like warping, hardness, and occasionally thickening. Without silicon, plants may have less structural integrity and be more prone to pests and diseases (Xu et al., 2023). Soft and drooping leaves and culms, decreased photosynthetic activity, decreased grain yields, and a rise in diseases like blasts and brown spots are some of the symptoms that affect rice plants.

Additionally, plants lacking in silicon may be more prone to lodging (Berahim et al., 2021; Ngugi et al., 2022). The deficiency symptoms manifest as tiny, circular white spots called freckles. In gramineous plants, Si deficiency causes stalk weakening and crop lodging. To correct Si deficiency, granular silicate fertilizers like calcium silicate at 120-200 kg/ha or potassium silicate at 40-60 kg/ha are applied (Das, 2014). Recycling rice straw (5-6% Si) and rice husk (10% Si) is also a good practice (Mirmohamadsadeghi and Karimi, 2020). Since plants can only absorb silicon in the form of silica acid, these are mostly utilized for foliar applications. It aids in the defence of plants against insects-pests and diseases, including powdery mildew, septoria, and eye spots, among others (Wang et al., 2017). Liquid fertilizers can be sprayed on leaves and applied to the soil via foliar irrigation or fertigation systems.

Selenium

Activation of antioxidant enzymes selenium enhances the uptake of valuable substances, stabilizes the plasma membranes, and makes various antioxidant enzymes active, which help plants to cope with abiotic stress (Gaikwad et al., 2020; Liu et al., 2022). Although plants typically only need small levels of selenium, it is essential for plant growth. Selenium deficit can happen in some areas where the soil has low quantities of the element, even though it is less prevalent than shortages in other vital elements. Selenium deficiency symptoms can lead to stunted growth, chlorosis, necrosis and reduced fertility, resulting in less yield (Gupta and Gupta, 2017). Plants usually need only a tiny amount of selenium, which varies depending on how much selenium is in the soil where they grow. Too much selenium can harm plants and cause selenosis (Gupta and Gupta, 2017). According to studies, the highest total Se concentration was found in rice seeds treated with foliar spray with sodium selenite (Na_2SeO_3), primarily related to inorganic Se (Yin et al., 2019). Adding naturally occurring, high-selenic organic compounds or amendments can help compensate its deficiencies (Kumar et al., 2024). Foliar application is dousing plants' leaves directly with a selenium-containing solution, and it is a beneficial method for giving a rapid boost of selenium, particularly in cases where the insufficiency is severe.

Correction of deficiency with a special reference to foliar application of nutrients

Biologically enhancing any specific nutrients in the edible portion is known as biofortification. It is employed in several food crops, such as rice, wheat, corn, pearl millet, and legumes. Since these seedlings also have better survival power and tolerance to disease and other environmental problems, mineral-packed seeds substantially enhance agricultural productivity in underdeveloped countries in an environmentally friendly way. Biofortification can be divided into two types such as genetic biofortification and agronomic biofortification. A sophisticated agricultural technique called genetic breeding attempts to change the genetic makeup of a crop to increase its nutritional value. Their nutritional value is achieved by identifying and manipulating specific genes. This can be achieved using traditional breeding methods or cutting-edge genetic techniques such as CRISPR-Cas9. The aim is to grow, in addition to high agricultural production, plants rich in essential vitamins and minerals. Scientists are working to develop biofortified crops that can significantly reduce food and nutritional insecurity for poor people by targeting genes that regulate food quality. Most biofortification strategies focus on transgenic approaches or plant breeding (White and Broadley, 2009). However, genetic biofortification has some constraints like complex genetic architecture, trait stability, public acceptance and perception, gene flow and contamination, ecosystem impact, intellectual property rights, dietary preferences, and adoption by small farmers.

Another way of biofortification is agronomic biofortification, which farmers can adopt easily. Agronomic biofortification includes seed priming, soil application, and foliar fertilization. The preparation or propagation of viable seed material only for ingestion and absorption with a solvent or water is known as seed priming. This allows the seeds to use micronutrients effectively and efficiently and become sensitive to future deficiencies. Seed-coating micronutrients and other substances are added to the seed before it germinates and grows and develops into a plant. In this case, the initial push enables the seed to resist hidden hunger and gain immunity. These strategies include enhancing the final products through biological processes or enhancing their value through nutrient-rich additives, consuming nanoparticles and other micro-molecules containing essential nutrients, and injecting micronutrients directly into plant roots. Typically, this process involves the application of fertilizers specifically containing micronutrients or soil amendments to increase plant availability, e.g., in nutrient-poor soils. Soil application has the potential as nutrient runoff, which occurs when it rains and washes a lot of applied inputs into the surrounding water, causing eutrophication and pollution of water.

Furthermore, fertilizers applied in the soil may eventually change the soil's chemical properties, which would be detrimental to the soil's microbial activity and nutrient availability. Another disadvantage is that particular soil types may make it more difficult for plant roots to acquire nutrients, which could lead to inadequate nutrient uptake by plants. For example, potassium leaches out of the soil easily because of its mobility under low pH and phosphorus precipitates. Considering these above constraints, adopting an alternative approach that can limit these constraints without impairing the benefits of soil application is imperative. Under these contexts, the foliar application is gaining wide recognition (Ray and Sairam, 2024).

Foliar fertilization is more valuable and practicable if mineral elements are challenging to transport to edible tissues. It helps easily and quickly absorb nutrients through cuticles and stomata. Foliar fertilization is typically applied to promote disease resistance, growth, nutritional status control, and the quality of the resulting crop by speedily correcting deficiencies (Table 1). Supplementing crops with foliar nutrition improves crop growth and raises yield quality and the quantity of minerals in the edible part of crops.

Table 1. The beneficial effects of foliar fertilization in cereals.

Element	Crop	Research findings	Reference
Zinc	Rice	Foliar spray of zinc oxide nano particles (12.00 kg/ ha) increased grain production by 2.3% to 4.1% as compared to the control because of higher spikelets (7.4% to 9.2%), filled grains (1.7% to 4.3%) and test weight (4.2% to 7.1%) in the treated plot.	Wang et al., 2023
		The findings showed that foliar application of zinc at various developmental stages greatly increased rice crop productivity. Zn application (0.5%) during the booting and milking stage resulted in enhanced kernel weight (25.50 g and 25.61 g) and kernel yield (5.45 t/ha and 5.44 t/ha) during 2015 and 2016 respectively.	Chattha et al., 2023
		The curtailment of one-thirds of the recommended NPK fertilizer and foliar spray of nano zinc (@50 mg/L at booting stage significantly increased the number of grains/panicle (80 and 81.67) and percentage of filled grains (88 and 87 %) and there was non-significant difference with the recommended dose of NPK during 2019 and 2020 respectively.	Elekhtyar and AL-Huqail, 2023
		The highest grain yield (9.06 t/ha) and straw yield (10.51 t/ha), harvest index (46.50), panicle length (11.96 cm), protein % (8.96 %), and Zn content (42.76) were obtained by fertilizing Giza 178 with foliar application of Zn at a rate of 2,500 mg/L.	Kandil et al., 2022
		The maximum grain production of 5.09 t/ha was obtained by foliar treatment of 0.5% $ZnSO_4$ at panicle initiation stage and a week after flowering which resulted 50.59% higher grain productivity than the control (3.38 t/ha).	Saikh et al., 2022.
		The application of graded levels of zinc oxide nano particles (30-60 kg/ha) resulted in a higher rice productivity compared to the control, with 4.83–13.14% higher panicles, 4.81–10.69% more spikelets per panicle and 0.28–2.36% greater filled grains.	Zhang et al., 2021

		In comparison to BRRI dhan 52 without the treatment of zinc, BRRI dhan 52 with zinc application (3 kg/ha) demonstrated the highest plant height (84.01 cm), effective tillers/ hill (8.33), 1000 grain weight (25.07 g), grain yield (4.62 t/ha), and straw productivity (4.86 t/ha).	Islam et al., 2021
	Maize	Zinc fertilization increased 17% grain yield (1 t/ha) and 25% Zn content in grain (7.19 mg/kg) through Zn fertilization over the control.	Mutambu et al., 2023
		When 0.1 % Zn-EDTA was applied as foliar spray, the plant height (155 cm), cob diameter (4.2 cm), cob length (17 cm), and kernel row (13 cm) increased compared to the control.	Hisham et al., 2021
		The application of graded level of Zn (34.1 kg/ha as 150 kg/ha of $ZnSO_4 \cdot 7H_2O$) to the soil raised the yield of maize by 4.2-16.7%.	Liu et al., 2020
	Wheat	The application of zinc at a rate of 10 kg/ha enhanced in grain yield (1397 kg/ha), straw yield (3276 kg/ha), and zinc content in grain (23.41 mg/kg) and straw (18.64 mg/kg).	Kumar et al., 2022
		The application of Zn to the genotypes of triticale (TL 2942) and bread wheat (PBW 343U) showed an increase in grain and straw yields (48.2% and 68.4%, respectively) over the control. Zn concentrations in grain and straw reached its peak in the bread genotype PBW 621 (51.2%) and durum genotype HD 2967 (68.5%) compared to the control.	Dhaliwal et al., 2022
		The foliar application of 5 kg/ha nano-zinc resulted in an increase in the mean number of tillers (371/m^2), plant height (104.4 cm), spike length (10.4 cm), number of spikelets/ spike (19), number of grains/ spike (48), 1000 grain weight (37.7 g) and grain productivity (3.98 t/ha).	Hafeez et al., 2021
		A single Zn spray (1.12 kg Zn/ha) at heading increased Zn content in grains ranging from 5.8 to 9.5 mg/kg, which is equal to 17–47% enhancement over the control.	Afshar et al., 2020
	Barley	In comparison to the control, the application of zinc (4 kg/ha) enhanced the plant height (84 cm), tillers per plant (7), spike length (8 cm), test weight (39 g) and grain yield (3775 kg/ha).	Ishaq et al., 2018
Iron	Rice	The foliar application of 0.5% $FeSO_4.7H_2O$ resulted in a significant rise in the number of tillers/m^2 (419), panicles/m^2 (378), test weight (18.83 g) and grain productivity (4628 kg/ha), over the unfertilized control in iron deficient sandy loam soil of central Gujarat.	Abhishek et al., 2023
		The soil + foliar application of iron (3.25 kg/ha) fertiliser produced the highest numbers of panicles/hill (13.30), grains/panicle (126.73), filled grain (93.92%), 1000 grain weight (27.90 g), and grain productivity (3555 kg/ha) in comparison to the control.	Butsai et al., 2022
		When 1.5% $FeSO_4$ was applied during tillering, booting, and before flowering, the plant height (58.04 cm), root length (4.14 cm), spikelet number (9.00), number of filled grains/panicle (238), 1000 seed weight (28.50 g), grain productivity (2470 kg/ha), and straw yield (3455 kg/ha) showed higher values than the control.	Baishya et al., 2019

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		The foliar spray of 2.0% iron sulphate for three times resulted in an increase in plant height at harvest (106.12 cm), tillers per m^2 (388.7), dry matter production (1229.8 g/m2), and grain yield (5.26 t/ha) of rice compared to untreated crop.	Kumar et al., 2018
	Wheat	The sole application of iron (12 kg/ha) resulted in an increase in the mean number of tillers (365/m^2), plant height (103.7 cm), spike length (10.2 cm), spikelet number (19/spike), grains per spike (47), test weight (36.1 g), grain productivity (3.84 t/ha) in semi arid conditions.	Hafeez et al., 2021
Boron	Rice	In comparison to the control plot, foliar treatment of boron (borax pentahydrate at 500 l/ha) produced maximum filled grains (90.9%), and boron concentration in grain (15.4 mg/kg).	Songsriin et al., 2023
	Maize	Soil application of B at the rate of 0.5 kg/ha + foliar spray (15 ppm) resulted in significantly higher plant height (186 cm), dry weight (188 g/plant), cobs/plant (1.34), seeds/row (29.36), rows/cob (14.73), test weight (216 g) seed yield (7.7 t/ha), stover yield (12.3 t/ha) compared to untreated control.	Priyanka et al., 2022
	Wheat	The highest spike length (12.7 cm), grains/spike (50), test weight (35 g), biological yield (9.9 t/ha) and grain yield (4.7 t/ha) were obtained by foliar spraying of 1.5% B solution in comparison to the control plot.	Saleem et al., 2020
	Barley	When comparing the results to the control, the 2% foliar spray of B exhibited the highest values for all the examined traits such as weight growth per spike (6.2%), plant height (5.6%), tillers per plant (2.4%), spike length (32%), seed index (6%) and grain productivity (10%).	Ahmad et al., 2021
Sodium	Rice	Compared to the control, the application of sodium para-nitrophenolate 0.3% SL @ 2% a.i., or 20 ml/L formulation, significantly enhanced the growth attributes of both boro and kharif rice.	Das et al., 2022
Silicon	Rice	At the tillering, panicle initiation, and grain formation stages, a foliar spray of 1.0% potassium silicate produced noticeably higher yields of grain (4.713 t/ha) and straw (6.475 t/ha) than the control.	Shah et al., 2022
	Maize	The results showed that 150 kg/ha of active silica treatment resulted in considerably greater numbers of rows/cob (11.47), grains/row (22.42), test weight (211.78 g), grain (2816 kg/ha), stover (4349 kg/ha), and biological yield (7165 kg/ha).	Prajapat et al., 2021
	Wheat	Foliar application of 2% K_2SiO_5 decreased the damages due to drought conditions while increasing the chlorophyll-a (1.21), chlorophyll-b (0.64), flag leaf area (45 cm^2), plant height (124 cm), number of nodes per plant (5.3), tiller height (99.4), number of tillers/ m^2 (276.3), spike length (12.9 cm), number of spikes/ plant (14.3), number of grains per spike (38.3), test weight (44.3 g), total dry weight/ plant (385 g) and grain yield (5074.8 kg/ha) in comparison to the control.	Aurangzaib et al., 2021
Selenium	Rice	When applied as a foliar spray at a rate of 20 mg/L of Se under drought stress, there was an increase in the number of filled grains, number of grains, and grain yield by 22.0, 4.3 and 11.0%, respectively, compared to water spray considered as control.	Patnaik et al., 2023

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	Maize	The results of pot culture with the application of 2.5 mg/kg soil indicated the highest values for shoot length (113.67 ± 1.86 cm), shoot fresh weight (79.00 ± 1.53 g), shoot dry weight (16.95 ± 0.03 g), and root fresh weight (24.00 ± 0.53 g) as compared to control at 60 days after sowing.	Naseem et al., 2021

Physiology of absorption of sprayed nutrients by plants

The primary method by which plants absorb macro- and micronutrients is via their roots; nevertheless, reduced root absorption may often happen as a result of nutrient availability limitations. There is a lot of data to support the absorption and transfer of nutrients given topically (Alexander and Schroeder, 1987; Oosterhuis, 2009; Fernández and Brown, 2013; Etienne et al., 2018; Alaoui et al., 2022). Foliar fertiliser spraying is a standard practice in agriculture to improve the nutritional status of plants (Mengel, 2002).

Cuticles are generally thought to be the rate-limiting process of leaf penetration. Exogenous substances can enter the symplast from the leaf surface by two different routes: through the water channel and lipoids. Lipid-soluble substances enter the cuticle in a largely nonpolar, undissociated state, while molecules that enter with water penetrate slowly and benefit from a highly saturated environment. Most of the absorption occurs by passive diffusion, mainly through the lipoid image, and the rest occurs by a dynamic absorption process that depends on the plant and its metabolic activity. Passive diffusion is the primary mechanism by which foreign chemicals penetrate the cuticle and underlying membranes (Ossola and Farmer, 2024). There is a visible gradient from low to high charge density between the hydrophilic inner walls and the hydrophobic outer surface. Thus, ion penetration through the cuticle is promoted along this gradient, which is necessary for leachate losses and leaf mist uptake. The cuticle layer is a weak cathexis because of unsterilized cutin polymers and the pectin material's negative charge. According to earlier research, solutes travel through non-plasma channels called cochlea or ectoderm in the cuticle and have a less stiff fibrillar structure than other wall parts. A rough reticulum of cellulose fibrils that fills these bundles of interfibrillar gaps that extend from the plasmalemma into the cuticle can serve as polar channels for leaf secretion and absorption. It is well known that plant cuticles have a network of hydrophilic channels that let water and tiny dissolved substances like minerals and carbohydrates pass through.

Larger molecules like synthetic chelates cannot easily pass through most of these cuticular pores. At the same time, smaller compounds like urea (radius 0.44 nm) can have a diameter of more than one nanometer and a density of roughly 1010 holes/cm. Cations are aided in moving down this gradient by the negative charges surrounding these pores, which thicken from the outside of the cuticle. For this reason, cations are absorbed more quickly than anions, exceptionally tiny uncharged molecules like urea. The most significant number of cuticular pores, which serve as cuticular transpiration channels, are found between guard and lateral cells in the cell wall system. The concentration gradient of the electrochemical gradient from outside the cell plays a crucial role in the assimilation of solutes into the cell's interior following a cuticle breach. However, the plasma membrane's permeability coefficient is also significant in entering substances and the rate at which the cells absorb them. When fertilizer nutrients are given to leaves, they have the potential to evaporate into thin air, crystallize and stay on the plant's exterior, disappear from the leaf due to dewdrops, or be absorbed and stay in solution on the treated leaf and cuticle. The lipoid penetrates the cuticle and then moves into the aqueous phase of the apoplast, diffuses into the internal structure of the leaf, and finally moves from the leaf through the stem (Oosterhuis and Weir, 2010; Zeisler-Diehl et al., 2018). After the leaf cells have absorbed the solutes, they can continue through the apoplastic or symplastic pathways into the vascular tissues. When nutrients are supplied locally, they enter the phloem through photosynthetic pathways and are assimilated.

These days, increasing foliar absorption and nutrient utilization efficiency is one of the biggest problems for crop production (Al-Juthery et al., 2021). Its many benefits make it a popular choice for many crops and situations. Foliar fertilization speeds up plant nutrient absorption (Hu et al., 2023; Yadav et al., 2023). When it comes to providing essential nutrients to the plant, direct application to the leaves is the most effective method. Timely management of nutrient deficiency can effectively be managed by it. Foliar application of plant nutrients allows accurate application of nutrients required at a particular stage of growth or when plant needs are high to achieve maximum yield and quality. Foliar fertilization is a simple process that offers advantages such as faster application, increased efficiency, more

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accurate targeting, and reduced environmental impact. However, it has drawbacks such as limited plant nutrient absorption, sensitivity to external stimuli, leaf scorching, low effect on root growth, and possible utilization above. Foliar nutrient formulation is crucial for treating deficiencies and preventing phytotoxicity. Regular calibration of spraying equipment is essential.

Future scope of research and recommendation

High fertilizer dosages and inefficient crop utilization of micronutrients increase the quantity of nutrients in the soil to the point where they become pollutants and cause farmers to suffer significant financial losses that deter them from investing in the field. Farmers may readily implement foliar application of micronutrients. With the development of several types of latest formulations of plant nutrients, such as nano-fertilizers, chelated fertilizers, biofertilizers, and water-soluble fertilizers, which have better nutrient translocation to consumable plant parts and higher plant nutrient use efficiency, the efficacy of agronomic biofortification has increased recently. With the advent of several formulations of micronutrients, there is a need for the hour to carry out location- and crop-specific research for the highest nutrient-use efficiency. In this regard, the crops and cropping systems adopted must be taken into consideration. Further, various doses and crop stages are to be tested for different agroclimatic conditions and seasons to ensure the maximum benefits from foliar application of micronutrients.

Conclusion

Food and nutritional security are prime concerns for a hunger-free world. In the current context, a surging demand for mineral micronutrient supplantation and biofortification is considered one of the suitable options. The need-based foliar application of nutrients is cost-effective in combating hidden hunger in the form of micronutrient deficiency. Simultaneously, mitigation options related to policy decisions are to be implemented. Undoubtedly, foliar fertilization increases nutrient content in the cereal grains and protects against biotic and abiotic stresses. Foliar fertilization increases nutrient use efficiency, improves growth and development, and results in better produce while fulfilling the goals of agricultural sustainability and a hunger-free world. Further, foliar fertilization is a promising technique for agronomic biofortification, which can increase the health, well-being, food and nutritional security of the growing global population. Nonetheless, additional research is needed to optimize foliar fertilization frequency, timing and dosage for crops under various cropping systems and agroclimatic conditions while keeping bioavailability and agricultural sustainability as the primary goals.

Conflict of interest

All authors declare that there is no conflict of interest.

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