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Biofortification of Iron and Zinc in Field Crops Through Plant Microbe Interaction: A Review

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ABSTRACT

Micronutrient deficiency is a big concern around the world since it causes serious social and health problems. Micronutrient availability is low on millions of hectares of land around the world, including India. Zn deficiency in Indian soils has reached 47% and Fe deficiency has reached 13%. The main causes of micronutrient deficit in soil are excessive fertilizer use (over the RDF), soil erosion and other agronomic practices that obstruct the movement of micronutrients. A promising and sustainable agriculture-based method called biofortification aims to reduce Zn and Fe deficiencies in dietary food ingredients. The plant breeding method to create biofortified crops and agronomic supplementation of micronutrients, such as foliar/soil application together with chemical fertilisers, have drawn the most attention among the various strategies used. Interactions between plants and microbes are recognised to be essential for enhancing the nutrient status of the soil and enriching micronutrients through the solubilization, mobilisation and translocation of metals to various parts of the plant. This symbiotic relationship enhances the quality and yield of crops, while innovative food processing techniques can offer cost-effective biofortified food solutions to address the nutritional needs of undernourished populations.

Key words: Biofortification, Micronutrients, Nutrient deficiency, Plant microbes, Sustainable agriculture.

The cornerstone to good health is healthy nutrition, which strongly depends on sustainable agriculture (WHO, 2018). The need for high-quality food has arisen as a result of the world's population growth (United Nations, 2017), which is predicted to reach 9.8 billion people by the end of 2050. Unfortunately, the quality component has been disregarded in favour of manufacturing more food. Undernourishment is a serious issue today. Scientists from all fields, including health, nutrition, economics, tourism and agriculture, are paying close attention to the global problem of micronutrient deficiencies that are producing a variety of nutritional problems (Athar *et al*., 2020). There is an urgent need to comprehend the degree of micronutrient deficiencies in soils and how they affect crop physiology in order to comprehend the relationship between micronutrient supply and human health. Micronutrient availability is low on millions of hectares of land around the world, including India. Zn deficiency in Indian soils has increased to 47% and Fe deficiency has decreased to 13% (Singh and Prasanna, 2020). There are significant differences in Zn deficiency severity between soil types and Indian states. In India, the extent of deficiency of Zn is to the tune of 86% in Maharashtra, 72.8% in Karnataka, 60.5% in Haryana, 58.4% in Tamil Nadu, 57% in Meghalaya, 54% in Bihar and Orissa, 49.4% in Andhra Pradesh and 48.1% in Punjab (Fig 1) (Singh and Prasanna, 2020). Fe deficiency-mediated interveinal chlorosis in crops is a widespread phenomenon in arid and semiarid soils or calcareous soils worldwide, including India, which causes a significant loss in yield. In India, Fe is mainly deficient in the soils of Karnataka (35%), H.P. (27%), Maharashtra (24%), Haryana (20%), Tamil Nadu (17%) and Punjab (14%) (Shukla *et al*. 2015) (Fig 2). Micronutrients are crucial for the growth and development of plants, as well as for the maintenance of good human and animal health. The two biggest issues endangering the lives of millions of people in developing countries are poverty and a lack of food. Low soil micronutrient availability not only affects crop yields but also causes the edible components of crops to have poor nutritional value, which causes malnutrition in human populations, especially in developing and underdeveloped nations (Hurst *et al*., 2013; Kumssa *et al*., 2015). Iron (Fe) and zinc (Zn) deficiencies affect 60% and 30% of the world's population, respectively (Kaur *et al*., 2020). The micronutrient deficiencies affects mostly children world life. Birth defect, cancer, cardiovascular illness, osteoporosis and neurological abnormalities, among other conditions. Increasing the availability of micronutrients in the soil, which is regarded as a foundational element of agriculture, is the

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first step in the biological process of micronutrient improvement (Ahmad *et al*., 2016). Microbes offer a novel and promising approach to biofortification, which complements and enhances traditional breeding and agronomic practices. Microbes can help in biofortification in comparison to agronomic practices like targeted nutrient uptake, solubilization of nutrients, production of plant growth regulators, reduced dependency on external inputs (Unlike agronomic practices that may require the application of chemical fertilizers or other supplements), environmental benefits and long lasting impact. As a result, the main focus of this study will be on the signs of Zn and Fe insufficiency in both plants and people, the health issues caused by unrecognised hunger and the contribution of modern agriculture to the production of nutritious products.

Biofortification and its need

The technique of increasing the micronutrient content in staple crops is called bio fortification which aims to improve the nutrition of human health. Microbe-mediated biofortification is a highly encouraging and promising method for increasing the bioavailability of micronutrients to plants, primarily due to its cost-effectiveness. This novel approach offers a potential solution for enhancing the nutrient uptake and enrichment of crops through the beneficial interactions between plants and microbes.

Over the past 50 years, agricultural research has made significant strides in improving the productivity and output of staple crops, such as rice, wheat, maize, pearl millet and others, particularly in developing countries. However, this progress has come with a trade-off-the micronutrient content of these crops has been significantly reduced (Bouis and Saltzman, 2017). The focus of agriculture research during recent decades has largely been on developing high-yielding crop varieties and intensive cropping systems, often relying on imbalanced use of chemical fertilizers to increase food grain production and meet the growing global food demand. Unfortunately, this emphasis on yield enhancement has led to a decline in the micronutrient content of crops.

As a consequence, a major global concern known as “hidden hunger” has emerged, affecting more than two billion people worldwide. Addressing this challenge of hidden hunger requires a shift in agricultural research priorities. There is a growing recognition of the need to develop crop varieties and farming practices that not only prioritize high yields but also pay attention to the nutritional quality of the crops. This approach, known as biofortification, focuses on increasing the micronutrient content of crops through microbe-mediated strategies, without compromising their productivity.

Causes of micronutrient deficiency in soil

Table 1 provides an overview of the causes of various micronutrient deficiency in soil, highlighting the diverse

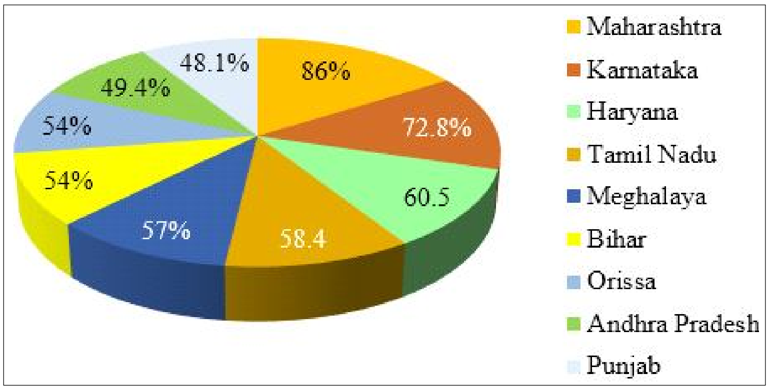

Fig 1: Magnitude of Zn deficiency in states in India.

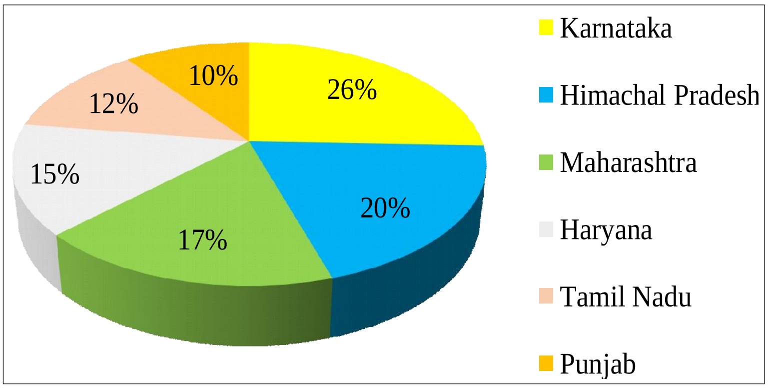

Fig 2: Magnitude of Fe deficiency in states of India.

factors that can impact the availability of micro nutrients for plant growth. Micronutrient deficiencies in soils are brought on by a variety of environmental and edaphic conditions, including soil organic matter concentration, pH, cation exchange capacity, clay content etc. The bioavailability of micronutrients is impacted by calcareous soils or soils that are more prone to waterlogging (Ramzan *et al*., 2014). Micronutrients are absorbed and precipitated at high soil pH, high $CaCO_3$, low organic matter and low soil moisture, rendering them unavailable to plants. For instance, a significant portion of the Fe found in the earth's crust exists as Fe3+, which is inaccessible to plants. The more soluble form of iron, Fe2+, is easily converted into the ferric form, Fe3+, which precipitates in the soil in the forms of oxide/ hydroxide, phosphate, carbonate and other inaccessible complex forms (Singh and Prasanna, 2020).

These causes can significantly impact the bioavailability of micronutrients, affecting their uptake and utilization by plants and subsequently leading to deficiencies.

Role of microbes in biofortification

Microbes play a crucial and diverse role in biofortification by exerting influence on various factors, as outlined in Table 2. Both below and above ground, microbes and plants have coevolved and are physiologically and ecologically intertwined. They play a crucial role in the cycling of nutrients by decomposing and mineralizing organic matter as well as converting inorganic minerals into forms that are readily available (Rana *et al*., 2012). By chelation, solubilization and oxidation/reduction reactions in soil, plant growth-promoting microorganisms (PGPM) such as bacteria, cyanobacteria, fungi and mycorrhizae can also influence plant growth and the availability of nutrients (Adak *et al*., 2016). Additionally, when bacteria interact with plant roots, root exudates are released and can affect a variety of soil variables, including soil pH (Batool *et al*., 2021). Consequently, using microorganisms as biofertilizers and phytopathogen antagonists offers a viable alternative to chemical fertiliser and pesticide and it is also a practical and affordable strategy. Fe and Zn are thought to be more crucial micronutrients for biofortification. According to Singh *et al*. (2020), microorganisms can increase the availability of Zn and Fe in soil, improve their mobilisation in plant parts, or raise the bioavailability of Fe and Zn in food grains through a variety of methods. They consist of the following:

- ✓ Production of siderophores.
- ✓ Organic acid secretion.
- ✓ Modification in root morphology and anatomy.
- ✓ Secretion of enzymes.
- ✓ Reduction of phytic acids or anti-nutritional factors in food grains.
- ✓ Production of phytohormones/IAA.
- ✓ Solubilization and uptake of micronutrients.

Production of siderophores

Siderophores are low molecular weight Fe chelating compounds that have high affinity toward Fe (III). It is produced by rhizosphere bacteria that may enhance plant growth by increasing the availability of iron near the root or by inhibiting the colonization of roots by the harmful microbes (Jha and Saraf, 2015). Based on their structural features, siderophores can be divided in two groups; hydroxymates and catecholates. High affinity iron transport systems in general are made up of certain components, which includes siderophores, outer membrane receptor proteins, periplasmic binding proteins, ATP-dependent ABC-type transporters and the TonBExbB- ExbD protein complex, each is vital to the success of the transport system (Patel *et al*., 2018). Patel *et al*. (2018) reported that *Pantoea dispersa* MPJ9 and *Pseudomonas putida* MPJ6 isolates were found potent as iron chelating rhizobacteria which possessed high siderophore activity and in pot study they observed that bio-inoculum treated plants significantly increased vegetative parameters, iron content, protein, carbohydrates as compared to un-inoculated plants, indicating that use of siderophore producing isolates could result in enhancement of iron content of the mungbean. Kushwaha *et al*. (2021) revealed two potential ZSB (BT3 and CT8) based on their zinc solubilization index and zinc solubilization efficiency and these bacterial strains showed similarity with *Bacillus altitudinis.* These isolates also showed plant growth-promoting traits such as production of indole acetic acid (IAA), ammonia and siderophores. Inoculation of isolates BT3 and CT8 improved the growth parameters of chickpea and increased the plants Zn uptake by 3.9-6.0%. *B. altitudinis* strains (BT3 and CT8) show excellent capabilities to solubilize insoluble Zn compounds like oxides, phosphates and carbonates of Zn, making them valuable source for improving Zn uptake and growth of chickpea.

Table 1: Causes of micronutrient deficiency in soil.

Micronutrient	Causes of deficiency
Iron (Fe)	High soil pH, waterlogging, excessive lime application
Zinc (Zn)	Low soil pH, high phosphorus levels, soil compaction
Manganese (Mn)	High soil pH, excessive calcium or magnesium levels
Copper (Cu)	Acidic soils, high organic matter content
Boron (B)	Sandy soils, high rainfall, excessive leaching
Molybdenum (Mo)	High pH, low organic matter content
Chlorine (Cl)	Generally not common, excess chloride-sensitive crops

Organic acid secretion

PGPM enhance organic acid production in the root exudates (Zhang *et al*., 2014). Root exudates help in the precipitation of heavy metal ions by binding and absorbing metal outside the root. Production of organic acids in the root exudates leading to changes in the soil pH, proton extrusion by rhizospheric microorganisms, production of phytohormones such as auxin, ethylene and gibberellic acid, have all been implicated in the enhanced uptake of iron and zinc (Kobayashi and Nishizawa, 2012; Chen *et al*., 2014). Inoculation of endophytes resulted in the production of oxalic acid in root exudates (Singh *et al*., 2017). Inoculation with zinc solubilizing bacteria *Pseudomonas* sp. MN12 improved photosynthesis, yield, biofortification of grains and organic acid production in root exudates of bread wheat. Maximum pyruvic acid and tartaric acid concentration recorded for soil application of Zn + MN12 (Rehman *et al*., 2018). The strains MDSR7 and MDSR14 (Zinc solubilizing bacteria) produced substantially higher soluble zinc content with significant decline in pH and increase in total organic acid production was identified by Ramesh *et al*. (2014). The larger occurrence of AMF could have determined an acidification of the rhizosphere due to the higher release of organic acids and phenolic compounds with the increases of soil Fe availability in chickpea (Elisa and Stefano, 2014).

Modification in root morphology and anatomy

Plant growth-promoting rhizobacteria (PGPR), including endophytic and rhizospheric bacteria, are beneficial bacteria that colonize root surface and stimulate the growth of the host (Miransari, 2011). The usage of PGPR in agriculture is steadily increasing because it offers an attractive way to reduce the use of chemical fertilizers, pesticides and related agrochemicals (Bhattacharyya and Jha, 2012). For example, endophytic bacteria were implicated in supplying biologically fixed nitrogen in non-legumes, thus increasing the nitrogen economy of crop plants and reducing the requirement for N fertilizers. Improved root morphology and plant growth of rice was observed after inoculation with endophytic strains especially SaMR12 and SaCS20 (*Sphingomonas sp*.) and endophytic inoculation with SaMR12 and SaCS20 increased Zn concentration in roots and shoots. Stereomicroscope imaging of single roots showed that endophytic inoculation

Table 2: Different factors influenced by microbes for biofortification.

Factors	Microbes	Crop	Micronutrient	References
Siderophore production	*Bacillus altitudinis*	Chickpea	Zn	Kushwaha *et al.* (2021)
	Pantoea dispersa and *Pseudomonas putida*	Mungbean	Fe	Patel *et al.* (2018)
Organic acids	*Pseudomonas*	Wheat	Zn	Rehman *et al.* (2018)
	Zinc-solubilizing Endophytes- *Arthrobacter sulfonivorans* and *Arthrobacter* sp.	Wheat	Zn and Fe	Singh *et al.* (2017)
	Bacillus aryabhattai	Soybean	Zn	Ramesh *et al.* (2014)
IAA	*Bacillus altitudinis*	Chickpea	Zn	Kushwaha *et al.* (2021)
	Bacillus amyloliquefaciens	Wheat	Zn	Singh *et al.* (2021)
Zinc solubilization	*Pseudomonas aeruginosa*	Rice	Zn	Mishra *et al.* (2017)
	Bacillus altitudinis	Chickpea	Zn	Kushwaha *et al.* (2021)
	Bacillus aryabhattai	Soybean	Zn	Ramesh *et al.* (2014)
	Bacillus sp.	Soybean	Zn	Sharma *et al.* (2011)
Soil pH	*Bacillus aryabhattai*	Soybean	Zn	Ramesh *et al.* (2014)
	Bacillus altitudinis	Chickpea	Zn	Kushwaha *et al.* (2021)
	Exiguobacterium aurantiacum	Wheat	Zn	Shabnam and Meenu (2016)
Enzymatic activity	*Bacillus amyloliquefaciens*	Wheat	Zn	Singh *et al.* (2021)
	Funneliformis mosseae and *Rhizophagus irregularis*	Barley	Zn	Moshfeghi *et al.* (2020)
	PGPB (*Bacillus subtilis*) and AM fungi	Wheat	Zn, Cu, Fe and B	Yadav *et al.* (2020)
	Cyanobacteria	Rice	Zn, Fe and Mn	Adak *et al.* (2016)
	Plant growth promoting bacteria and cyanobacteria	Rice	Zn, Fe and Mn	Rana *et al.* (2015)
Root morphology	*Pseudomona Sps*	Chickpea	Zn, Fe and Mn	Gopalakrishnan *et al.* (2016)
	Endophytic microbes (*Burkholderia* sp.)	Rice	Zn	Wang *et al.* (2014)
	Zinc solubilizing endophytes (*Bacillussubtilis* and *Arthrobacter* sp.)	Wheat	Zn	Singh *et al.* (2017)

of SaMR12 and SaCS20 significantly stimulated root hair production (Wang *et al*., 2014). The root length, surface area, volume and diameter were further improved significantly through the inoculation of endophytes and the amount of Zn in grains due to inoculation of endophytes was two folds higher as compared to un-inoculated control (Singh *et al*., 2017). Gopalakrishnan *et al*. (2016) demonstrated SRI-229 strain was found to significantly and consistently enhanced yield traits including nodule number, nodule weight, shoot weight, root weight and grain yield for both chickpea and pigeon pea. When the harvested grains were evaluated for their mineral contents, iron, zinc, copper, manganese and calcium contents in chickpea and pigeon pea, were found enhanced in test bacteria inoculated plots over the un-inoculated control plots.

Secretion of enzymes

Soil enzyme activity is a parameter used to assess soil health. Soil dehydrogenase activity is used as an index of endogenous respiration in soil. There was a significant improvement in soil health parameters after harvesting the plants compared to the soil samples before sowing the seeds. Micronutrient content in wheat grains (Zn, Cu, Fe and B) was significantly higher in bacterial inoculated treatment compared to untreated control group (Yadav *et al*., 2020). Role of zinc solubilizing bacteria (ZnSB) on enzymatic activities to solubilize the insoluble form of Zn and in increasing Zn content in chickpea was reported by Batool *et al*. (2021). They selected six potential ZnSB (ZnSB7, *Paenibacillus polymyxa*; ZnSB11, *Ochrobactrum intermedium*; ZnSB13, *Bacillus cereus*; ZnSB21, *Streptomyces*; ZnSB24, *Stenotrophomonas maltophilia*; and ZnSB25, *Arthrobacter globiformi*) based on Zn solubilization halo, Zn solubilization efficiency and quantitative solubilized Zn. Seed inoculation of ZnSB13 exhibited maximum phosphatase, dehydrogenase and microbial activities in plant rhizosphere, thereby, caused a maximum availability of soil Zn. Furthermore, inoculation of ZnSB13 exhibited maximum increase in grain N, grain P and Zn contents in root, shoot and grains of chickpea. The influence of plant growth promoting bacteria (PGPB) and cyanobacteria, alone and in combination in rice and wheat crops indicated significant differences in soil dehydrogenase activity and micronutrient enrichment in grains (Fe, Zn in rice and Cu, Mn in wheat) (Rana *et al*., 2015). In barley crop the highest level of carbonic anhydrase enzyme activity was observed in inoculated with *F. mosseae* when sprayed with nano + ordinary ZnO and the lowest level of carbonic anhydrase enzyme activity was observed in the control treatment and resulted in highest Zn concentration in barley grain (Moshfeghi *et al*., 2020). Adak *et al*. (2016) reported that Anabaena bacterial-inoculated treatment exhibited notably higher enzymatic activities (peroxidase, chitosanase, endoglucanase and carboxymethyl cellulase) and increased levels of Fe (46.5%), Mn (67.2%) and Zn (32.6%) in the rice grains compared to the control treatment without bacterial inoculation.

Reduction of phytic acids or anti-nutritional factors in food grains

Phytate is the principal storage form of phosphorus (P) in seeds. It binds with minerals, proteins and vitamins and reduces their bioavailability (Elkhalil *et al*., 2001). Generally, the [phytate]: [Zn] ratio is an indicator of Zn bioavailability (Gibson, 2006). The study conducted by Magallanes-Lopez *et al*. (2017) on 46 durum varieties, the micronutrient and phytate content were analyzed to assess the potential bioavailability of these micronutrients. The research revealed significant variation in the phytate: zinc molar ratios among the varieties, ranging from 16.9 to 23.6, respectively. Endosperm is the major constituent of wheat flour and is low in Zn and phytate (Cakmak *et al*., 2010); thus, increasing the endospermic Zn concentration will increase the bioavailability of Zn in wheat grains. *Pseudomonas* sp. MN12 application reduced phytic acid concentration and showed better enhancement in grain Zn concentration and bioavailability in wheat (Rehman *et al*., 2018).

Production of phytohormones/IAA

The microbes synthesize biologically active compounds, including phytohormones (auxins, cytokinins, gibberellins and ABA), antifungal compounds, enzymes and compatible solutes. These microbial metabolites play a vital role in plant growth, nutrition and development (Sorty *et al*., 2016). A significant change in the IAA content was recorded in the rhizosphere of uninoculated control as well as in bioagents-inoculated plants under saline-sodic conditions at different time intervals and crop growth stages. Maximum IAA content was observed in the plants co-inoculated with *T. harzianum* UBSTH-501 and *B. amyloliquefaciens* B-16 at 90 DAS followed by 60 DAS. However, the least IAA content was recorded in uninoculated control at 120 DAS. it might be due to application of *B. Amyloliquefaciens* promotes plant growth by synthesizing plant growth hormones, such as indole-3-acetic acid (IAA), cytokinin and gibberellins; reduction in the volatile plant hormone, ethylene by the production of 1-amino cyclopropane-1-carboxylate (ACC) deaminase and through increased uptake of nutrients from the soil. IAA in the rhizosphere significantly increases root growth which constitutes a greater root surface area that enables the plant to obtain more nutrients from the soil (Singh *et al*., 2021). Two potential ZSB (BT3 and CT8) showed plant growth-promoting traits such as production of indole acetic acid (IAA) and zinc solubilization (Kushwaha *et al*., 2021). Fe, Mn, Cu, B and Zn content in wheat grain were significantly higher in foliar application of endophytic bacterial solution compared to un inoculated treatment. This might be due to production of ACC deaminase, phytohormones including auxins and gibberellic acid, nutrients solublization, nitrogen fixation activity and organic acids production (Yaseen *et al*., 2018). Bacterial isolates found positive for IAA production, a phytohormone responsible for increasing the length of the root hairs which could promote better absorption of nutrients from the soil.

Solubilization and uptake of micronutrients

The beneficial rhizosphere microorganism as bio- inoculant has been found to enhance the bioavailability of native zinc and this technology could be treated as low input sustainable agriculture (He *et al*., 2010) and to overcome zinc malnutrition in human populations (Mäder *et al*., 2010) could be a viable option. Hence, it is plausible that exploitation of native zinc mineralizing and solubilizing bacteria may aid in overcoming zinc deficiency and increase availability of zinc to crops. Application of zinc fertilizers based on nature of soil properties and nutrient interaction may cause reduced availability or convert into unavailable form. (Dhaliwal *et al*., 2019). These unavailable forms can be solubilized and transformed back into available forms *via* augmentation of microbial strains possessing the potential for Zn solubilization (Saravanan *et al*., 2007). Several plant growth-promoting rhizobacteria (PGPR) have major role in transforming insoluble Zn into soluble forms and make them available to plants for their uptake and thereby increase crop yield (Kamran *et al*., 2017). Zinc-solubilizing microorganisms can solubilize zinc from inorganic and organic pools of total soil zinc and can be utilized to increase zinc availability to plants. Fungi have been extensively studied for solubilization of insoluble zinc compounds both in vitro and *in vivo*. However, only some bacterial species of the genera Acinetobacter, Bacillus, Gluconacetobacter and Pseudomonas have been reported (Sharma *et al*., 2011). Four bacterial isolates were selected on the basis of their plant growth promoting abilities and their superior properties of solubilizing insoluble zinc compounds were exploited under i*n vitro* conditions in wheat and observed enhancement in Zn and Fe content (Shabnam and Meenu, 2016). Various mechanisms exerted by *Bacillus* for solubilization of Zn ores include proton extrusion, chelating ligands, organic acids, oxido-reductive systems, amino acids, vitamins and phytohormones. Zn solubilization is highly dependent on pH of the medium. Organic acids production is a key machinery to transform the insoluble form of Zn into a soluble one (Kushwaha *et al*., 2021). The co-inoculation of *R. tropici* + *B. subtilis* increased estimated Zn intake by 25.8% in 2019 and 15.8% in 2020, compared to the control. It might be due to inoculation of Zn solubilizing bacteria increased Zn partitioning and accumulation irrespective of Zn use efficiency and proved a sustainable and integrated strategy for grain biofortification and productivity of the common bean (Jalal *et al*., 2021).

Enhanced uptake of iron was observed by Sun *et al*. (2021) in wheat. This might be due to role of microbes on the chelation of iron by siderophores, production of organic acids in the root exudates or proton extrusion leading to changes in the soil pH, as well as production of phytohormones. Significantly higher Zn was observed in the root, shoot and grain of the microbial inoculated plants as compared to untreated control due to *Bacillus aryabhattai* solubilized the insoluble Zn present in the soil and made it available to the wheat and soybean plants. It was also reported that the application of PGPMs enhanced the translocation of Zn towards wheat grains through induction of physiological processes, mineralization and solubilization of Zn in the rhizosphere (Singh *et al*., 2021). The ZSB are involved in the increased bioavailability of Zn in plants through the solubilization of insoluble soil Zn fractions present in the rhizosphere. ZSB possibly increased the higher Zn availability during the grain filling stage, which increased the activity of source (flag leaf and stem) and thus more accumulation in grain (Ali *et al*., 2021). Kamran *et al*. (2017) reported enhanced bioavailability of zinc and mobilized it toward wheat grains due to enhanced uptake of nutrients upon inoculation with *P. fragi* strain.

CONCLUSION

In conclusion, while conventional breeding and agronomic biofortification techniques have shown effectiveness in improving micronutrient content in food crops, they have limitations in addressing all micronutrient deficiencies, such as iron and zinc. Moreover, the sustainability of these approaches requires continuous monitoring and support. To overcome these challenges and promote sustainable agriculture, a promising new strategy involves the use of microorganisms for biofortification. Microbes play a vital role in soil health and biogeochemical processes, making them valuable allies in enhancing the bioavailability of micronutrients to plants. Specifically, the application of Plant Growth Promoting Microorganisms (PGPM) as biofertilizers can significantly improve micronutrient supply, availability and uptake from the soil, supporting healthier plant growth and increased crop nutritional quality. One of the remarkable advantages of using microbial biofertilizers is their potential to reduce environmental contamination while offering an accessible and cost-effective solution for small and marginal farmers. This innovative approach not only helps combat hidden hunger and nutrient deficiencies but also promotes sustainable farming practices. Embracing the potential of microbe-mediated biofortification opens up new avenues to fortify crops with essential micronutrients, ultimately contributing to improved food security, nutrition and environmental conservation.

Conflict of interest: None.

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