Agronomic Biofortification with Se, Zn, and Fe: An Effective Strategy to Enhance Crop Nutritional Quality and Stress Defense—A Review

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Abstract

Human micronutrient deficiencies are a widespread problem worldwide and mainly concern people whose diet (mainly of plant origin) consists of insufficient amounts of critical vitamins and minerals. Low levels of micronutrients in plants are linked to, i.e., their decreasing concentration in soils and/or low bioavailability and presence of abiotic stresses which disturb the proper growth and development of plants. Agronomic biofortification of crops is a very promising way to improve the concentration of micronutrients in edible parts of crops without compromising yield and is recognized as the cheapest strategy to alleviate hidden hunger worldwide. The review is focused on the factors influencing the effectiveness of biofortified crops (a type of application, form, and a dose of applied microelement, biofertilizers, and nanofertilizers). Also, the accumulation of zinc, selenium, and iron in edible parts of crops, their effects on metabolism, morphological and yield parameters, and an impact on plants' defense mechanisms against abiotic stress like salt, high/low temperature, heavy metal, and drought was discussed. Finally, the directions of future agronomic biofortification studies are proposed.

Keywords Agronomic biofortification · Biofertilizer · Iron · Nanofertilizer · Plant nutrition · Selenium · Zinc

1 Introduction

It is estimated that more than 2 billion people (one in three) globally suffer from micronutrient deficiencies, also known as a “hidden hunger” (Prom-u-thai et al. 2020). These deficiencies are usually prevalent in highly developed countries and are more common among growing and developing children, pregnant and lactating women, sportsmen, and manual labor workers. Among the micronutrients, those most associated with micronutrient malnutrition worldwide are zinc (Zn), selenium (Se), and iron (Fe).

Researchers around the world continue their attempts to develop Se-, Zn-, and Fe-enriched food products to minimize their related deficiency disorders. Proper nutrition is key to good human health and according to the World of Human Organization (WHO), it mainly depends on sustainable agriculture (Athar et al. 2020). Unfortunately, current agricultural systems are still mostly oriented toward achieving high crop yields rather than nutritional quality, thus enhancing the concentrations of mineral micronutrients has become a key task in agriculture production. However, it is challenging to simultaneously increase the production of food enriched with essential micronutrients which does not cause obvious negative symptoms for plants like, i.e., limiting growth and productivity.

The reduced level of micronutrients in crops may be a consequence of different constraints like low levels or low bioavailability of essential elements in the soil (Manojlović et al. 2019), sub-optimal abiotic conditions including extremely high or low temperature, pH, water deficit, or anaerobic conditions, and also the presence of other elements (micro and macroelements and heavy metals). It was estimated that about 50% of cereals cultivated soils are Zn deficient. The Fe deficiency mostly occurs in calcareous (Jalal et al. 2020). Micronutrient deficiencies are more

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common in humid temperate and tropical regions where the intense leaching associated with high precipitation is observed. Another cause is the use of plant species with a low ability to accumulate sufficient quantities of micronutrients in their edible parts.

Biofortification is one of the ways to provide an increased level of micronutrients in crops (Huang et al. 2020). It has been shown that biofortified crops increase micronutrient intake and have a significant positive effect on human health (Bouis and Saltzman 2017; Praharaaj et al. 2021). There are three major approaches to biofortification: agronomic, conventional plant breeding, and plant breeding using genetic engineering (Garg et al. 2018). Among them, agronomic biofortification, which is aimed at supplying micronutrients that can be directly absorbed by the plant by application with mineral and/or foliar fertilizers and/or the improvement of the solubilization and mobilization of mineral elements in the soil, is recognized to be the simplest method used to enhance levels of microelements in crops. Agronomic biofortification is also recognized as one of the cheapest ways to reduce mineral deficiency in the human diet. Additionally, many reports evidence that biofortification, besides micronutrient enrichment of plants, also has a significant influence on the synthesis of other compounds that exhibit nutritional properties (Newman et al. 2021; Puccinelli et al. 2021b, 2019a; Skrypnik et al. 2019). For plants, application of Zn, Se, and Fe also effectively supports the fight with biotic stresses (Adrees et al. 2021; Noreen et al. 2020; Rizwan et al. 2019). The concentration range between the beneficial and toxic effects of Zn, Se, and Fe for crops is very narrow, thus a well-thought-out approach to choosing plant species for enrichment with microelements, strict selection concentrations and form in fertilizers, selection of appropriate type of fertilizer, and studies on the accumulation of these microelements by a specific species or even plant variety are necessary to obtain crops with high nutrition quality.

The paper covers the newest findings under agronomic biofortification with Zn, Se, and Fe. The first part of the review is focused on the main factors that determine the effectiveness of micronutrient biofortification. The next section provides some examples of the use of fertilizers based on nanotechnology and supported by microorganisms. The following section describes the beneficial effect of biofortification on increasing microelement content in edible parts of plants and also synthesis many compounds show health benefits. The last part of the paper discusses the influence of Zn, Se, and Fe biofortification on the alleviation of symptoms of abiotic stresses. In the conclusion section, the directions of future agronomic biofortification studies are proposed. The most important findings and information about conditions/type of experiments from collected research papers were presented in tables. Additionally, the enrichment factor (EF) was calculated. EF of the microelements was calculated as

a ratio of results obtained from the most advantageous fertilization of the crops ($C_{\max}$) in relation to the control group (C_{control}), according to the formula:

$$EF = \frac{C_{\max}}{C_{\text{control}}} \quad (1)$$

Estimation of EF was performed based on the data contained in the articles (in a numerical or graphical form).

2 Factors Influencing the Effectiveness of Biofortification with Zn, Se, and Fe Edible Parts of Plants

Many factors influencing the effectiveness of biofortification with Zn, Se, and Fe, including plant species, genotypes, and phenotypes; soil characteristics; type of application; and dose/form of applied micronutrients and climatic conditions have been widely investigated in recent years (Ebrahimi et al. 2019; El-ramady et al. 2021; Izydorczyk et al. 2021; Jones et al. 2017; Manojlović et al. 2019; Niyigaba et al. 2019; Ramzan et al. 2020; Smažiková et al. 2019; Sago et al. 2018). Most studies were performed under controlled conditions mainly on cereal, rice, grass, herbage, and corn (Ros et al. 2016). In this section, we discuss the types of applied fertilizers and the forms/doses of applied Zn, Fe, and Fe.

2.1 Type of Application

The application of micronutrients fertilizer to the soil is the most common practice and has been used for years; however, in addition to various limitations associated with soil properties, it should be mentioned that (i) applied fertilizers have a low recovery efficiency, (ii) this strategy requires regular application, and (iii) different granule size leads to uneven application of nutrients. Currently, much more attention is turned towards the application of foliar fertilization, where micronutrients are applied directly to plants leaves. It was found that the application of foliar Se fertilizer improved the durum wheat grain Se concentration twice in comparison with soil application at the same dose of Se (Galinha et al. 2014). On the other hand, Zn fertilization of wheat was the most effective for the application of combined soil and foliar fertilizers (Gomez-Coronado et al. 2016). In research on mungbean, the Zn grain concentration after application of 1.0% of solution of zinc sulfate was about 1.7 times higher (Haider et al. 2018a) than soil Zn application at a concentration of 10 mg kg⁻¹ soil (Haider et al. 2018b). However, it is worth noting that successful foliar fertilization requires, i.e., higher leaf area for better adsorption of the applied micronutrient. Additionally, this type of fertilization can

be limited by environmental conditions, particularly air temperature, wind speed and direction, rainfall, and relative humidity, and should be applied at the adequate stage of the growth and development of crops. For example, Wang et al. (2020b) suggested that the foliar application of Se in both forms (selenite or selenate) at the pre-filling stage has a greater effect on Se concentration in wheat grains in comparison to the application at the pre-flowering stage. Foliar spray of Zn and Fe was applied four times, one every 10 days in the flagging to grain filling stages in wheat (Jalal et al. 2020). Deng et al. (2017) proved that the concentration of Se in grains after application of both selenite and selenate at the full heading stage of rice was 2.9–3.5 times higher than at the late tillering stage. The best fertilizer effect for chickpea was obtained for application of zinc sulfate at sowing combined with foliar Zn application at flowering and pod formation stages (Pal et al. 2019).

Soilless cultivation represents a promising opportunity for the agricultural sector, especially in the regions characterized by soil degradation and limited water availability. For this reason, currently, more research is aimed at the enrichment of crops with micronutrients are performed under hydroponic conditions (Giordano et al. 2019; Puccinelli et al. 2019a; da Silva et al. 2020). Hydroponic cultivation has several advantages including, i.e., monitoring of nutrient concentration which in turn allows ensuring an optimal nutrient acquisition by plants without leading to nutritional disorders (Sambo et al. 2019). Skrypnik et al. (2019) noted that the application of Se to the nutrient solution had a significant effect on the essential oil content in basil leaves compared to foliar application.

Some authors suggested that the combined application of Zn, Fe, and Se soil and foliar fertilizers (Gomez-Coronado et al. 2016; Rivera-Martin et al. 2020) and fertilization with amendments like, i.e., biochar or salicylic acid (Ramzani et al. 2016; Smoleń et al. 2019) influenced a better efficiency for microelements accumulation in crops compared to when used separately. For example, it was found that Zn fertilization improved Fe concentration in grains (Niyigaba et al. 2019). The addition of microelements is usually applied in combination with the appropriate macronutrients fertilization (NPK). It is well-known that the plant's N status is an important factor influencing increased levels of Zn and Fe in vegetative tissue. A strong correlation between Zn and Fe grain concentration and urea application was found for wheat (Montoya et al. 2020) and chickpea (Pal et al. 2019). The foliar application of zinc sulfate in conjunction with urea significantly increased not only Zn uptake but also the total N uptake and the efficiency of urea N fertilization. Additionally, Gonzales et al. (2019) proved that application of Zn

fertilizer allows for a possible reduction of N application while maintaining barley grain yield and nutrition quality.

The impact of combined fertilization and its effects on plants are presented in Table 1.

2.2 Form and Dose of Applied Micronutrient

Application of appropriate form and dose of micronutrients has a significant effect on the accumulation of micronutrients in crops. The increase of soil zinc sulfate application increased Zn grain accumulation in wheat in the field study (Liu et al. 2017); however, Liu et al. (2019) noted that the percentage of Zn translocated from root to shoot decreased with increasing Zn application. In the study conducted by Gomez-Coronado et al. (2016), all of the tested wheat varieties (INIAV-1–10, Ardia, Nabao, Roxo) fertilized by soil Zn (applied as a zinc sulfate) at the concentration of the 50 kg h⁻¹ accumulated in grains about two times less Zn in comparison to results presented for wheat by Liu et al. (2019). Fertilization with Zn, which is usually applied as zinc sulfate, is the most commonly used fertilizer. The application of zinc sulfate not only improves the Zn concentration in edible parts of crops but also is the source of sulfur for crops (Persson et al. 2016). The presence of S-rich proteins is important for Zn storage in the endosperm and suggests a synergy of Zn accumulation due to S application. However, Montoya et al. (2020) suggested that the application of Zn in an organic form enhanced grain yield more than inorganic form (i.e., zinc sulfate), especially with recommended N rate. Márquez-Quiroz et al. (2015) indicated that application of complexes of Fe (Fe-EDDTA) is a more effective way to enhance the level of Fe in cowpea bean seed compared to an inorganic form. Se is usually applied as a selenate which is recognized as having more bioavailability for the plant than selenite (Li et al. 2018). It was found that at the same spraying stages, the grain Se concentration in rice was about two times higher for selenate than in selenite (Deng et al. 2017). However, there was no significant influence on grain yield and total biomass between the two forms of Se fertilizers. The soil fertilization with selenate caused the highest concentration of Se in radish in comparison to foliar fertilizer and selenite form application (da Silva et al. 2020). Contrary, Longchamp et al. (2015) noted that soil application of selenite could be attractive because selenite is less mobile than selenate and can enrich the soil in Se at each fertilization meaning that in the long term, plants grown on this soil will be enriched in selenium without the use of Se fertilizers.

An impact of the type of fertilization and trial, form, and doses of applied microelements is summarized in Table 2.

Table 1 Impact of combined fertilization on plant biofortification with zinc, selenium, and iron. The enrichment factor (EF) was calculated as a ratio of results obtained from the most advantageous fertilization of the crops in relation to the control group

Reference	Plant	Type of fertilizer/trial	Fertilizer	Highlighted findings	EF
(Montoya et al. 2020)	Wheat (<i>Triticum aestivum</i> L.)	Foliar/plot trial	Zn, N	Total grain Zn concentration significantly increased with increasing N application. The best results were obtained for the application of 120 kg N ha ⁻¹ and organic sources of Zn. The DTPA-extractable Zn content in soil was significantly higher for inorganic Zn sources	1.83 (grain)
(Gonzalez et al. 2019)	Barley (<i>Hordeum vulgare</i> L.)	Soil/plot trial	Zn, N	Zn and N fertilization increased Zn concentration and protein content in barley grain. Application of 90 kg N ha ⁻¹ and 10 or 15 kg Zn ha ⁻¹ resulted in the highest protein content in grains	1.43 (grain)
(Pal et al. 2019)	Chickpea (<i>Cicer arietinum</i> L.)	Foliar or soil or foliar + soil/plot trial	Zn, N	The highest grain yield, Zn, and Fe concentration in grains were obtained for the application of 25 kg Zn ha ⁻¹ applied at sowing combined with foliar spray of 0.5% Zn and urea at flowering and pod formation stages	1.1 (Fe grain) 1.20 (Zn grain)
(Smoleń et al. 2019)	Lettuce (<i>Lactuca sativa</i> L.)	Hydroponic/hydroponic trial	Se, I, salicylic acid	Accumulation of Se in plants varied depending on the variety. Combined Se with I and Se with I and salicylic acid significantly increased Se content in leaves. Among all doses of salicylic acid applied, application at 0.1 mg dm ⁻³ gave the best Se concentration in tested plants	95.22 (leaf)
(Leija-Martínez et al. 2018)	Lettuce (<i>Lactuca sativa</i> L.)	Hydroponic/hydroponic trial	Se, chitosan-polyacrylic acid	Chitosan-polyacrylic acid complex (5 mg Se plant ⁻¹) increased Se content up to 24 mg kg ⁻¹ d.w. and was no significant effect on the content of proteins, phenolic compounds, and glutathione and biomass in comparison to control	4.36 (leaf)

Table 1 (continued)

Reference	Plant	Type of fertilizer/trial	Fertilizer	Highlighted findings	EF
(Ramzan et al. 2020)	Wheat (<i>Triticum aestivum</i> L.)	Foliar or soil/plot trial	Fe, Zn	The combination of Zn and Fe foliar fertilization significantly increased the number of tillers, plant height, and spike length. The maximum tillers were obtained for a foliar spray of 0.5% ZnSO ₄ and 1% FeSO ₄ combined which showed statistical par with soil fertilization with of 12 kg of Fe ha ⁻¹ and 10 kg of Zn ha ⁻¹	1.68 (Fe grain) 1.41 (Zn grain)
(Jalal et al. 2020)	Wheat (<i>Triticum aestivum</i> L.)	Foliar/plot trial	Zn, Fe	The highest yield grain, Zn, and Fe concentrations were obtained for application of foliar 0.3% of Zn and 1% of Fe	N/A
(Niyigaba et al. 2019)	Wheat (<i>Triticum aestivum</i> L.)	Foliar/plot trial	Zn, Fe	The crude protein content of whole-grain after Zn and Fe foliar application (9.5 and 5.5 kg ha ⁻¹ ; 80% Zn + 20% Fe) was significantly improved in the second year of the experiment. Also, the Fe and Zn concentration in grains improved in the second year	1.5 (Zn grain) 1.61 (Fe grain)
(Mangueze et al. 2018)	Rice (<i>Oryza sativa</i> L.)	Foliar/plot trial	Zn, Se	Simultaneous spraying with Zn and Se foliar increased these minerals in rice grain/flour but had no significant effect on the yield and weight of 1000 grains. Lower use of selenium led to adequate Se levels, minimizing antagonism to Zn, Ca, S and Mo	N/A
(Sharma et al. 2019)	Soybean (<i>Glycine max</i> L.)	Foliar/plot trial	Fe, humic acid	The combination of Fe with humic acid improved yield and Fe concentration	1.21 (seed)

2.3 Special Fertilizer

2.3.1 Biofertilizer

Combining Zn, Se, and Fe in interaction with the application of plant growth-promoting bacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) is beneficial for the development of the environmentally friendly biofertilizers used for the production of crops enriched in microelements. PGPR mobilizes the nutrients by various mechanisms including acidification, chelation, the release of organic acids, and exchange reactions (Triticum et al. 2015). Furthermore, the mechanism also strictly depends on applied PGPR and the chemical form of micronutrients, i.e., oxides, phosphates, or carbonates. Among plant growth-promoting bacteria (PGPR), *Bacillus* is the most popular for microelements biofortification. *Bacillus aryabhattai* and *B. subtilis* were used to enrich maize in Zn (Mumtaz et al. 2018). The presence of *Bacillus* was found to enrich solubilization of unavailable Zn, as the microbial strains favor the formation of organic acids available for plants. As a result, the uptake of N, P, K, and Fe can also be improved resulting in increased root length, dry weight of the plant, and even chlorophyll content. However, Padash et al. (2016) observed a decrease in Fe level after solubilization of Zn with *Piriformospora indica*. *Bacillus pichinotyi*-YAM2, *Bacillus cereus*-YAP6, and *Bacillus licheniformis*-YAP7 were tested for Se and Fe biofertilizers in wheat (Yasin et al. 2015a, 2015b). In a study conducted by Padash et al. (2016), the inoculation of fungi *Piriformospora indica* with Zn increased Zn level in lettuce. Fungus *Rhizophagus intraradices* can increase the root adsorption surface via hyphae. Thus, a significant increase in Se content in shallot and chickpea was obtained (Golubkina et al. 2019, 2020), while *Pantoea dispersa* MPJ9 and *Pseudomonas putida* MPJ6 were used for mung bean biofortification with Fe, resulting in its content increase up to 100 mg dm⁻³ for MPJ9 after 60 days, when compared to control (30 ppm) (Patel et al. 2018). The positive effect on grain Zn concentration was observed for Zn inoculation with *Rhizophagus irregularis* above 150 mg Zn kg⁻¹ of soil (Tran et al. 2019). Further details about applications of Zn, Se, and Fe with microbes and impacts on microelements accumulation and physiological parameters of crops are presented in Table 3.

2.3.2 Nanofertilizer

Zn, Fe, and Se nanoparticles (NPs) can be synthesized in several ways. For example, Subbaiah et al. (2016) synthesized ZnONPs with a size about of 25 nm and negative zeta potential of 39.6 mV by oxalate decomposition technique. The chitosan and sodium tripolyphosphate were used for the synthesis of positive charge (42 mV) of the zinc complexed

chitosan NPs (Deshpande et al. 2017). In a study proposed by Hussein et al. (2019), the SeNPs with a size of about 10–30 nm were synthesized by mixed sodium selenite with ascorbic acid. SeNPs were also stabilized by polyvinylpyrrolidone (PVP) and ascorbic acid with a diameter of about 70 nm were studied by Siddiqui et al. (2021). The origin of Se formation at the nanoscale was characterized using spectrophotometer UV–VIS (peak at wavelength 400 nm described selenium formation at nano size). The application of Cu, Fe, and Zn NPs mixed with urea-modified hydroxyapatite (diameter about 38.21 nm) was studied by Tarafder et al. (2020).

Uptake, translocation, and accumulation of NPs depend on plant species and characteristics of NPs like size, chemical configuration, stability, and concentration. Du et al. (2019) showed inhibited effect of ZnONPs on the germination rate of wheat. By contrast, the same dose on ZnONPs has no significant effect on corn and cucumber germination with a significant decrease of root elongation (Zhang et al. 2015). In the study performed by Subbaiah et al. (2016), the highest germination percentage of corn was observed at 1500 mg dm⁻³ of ZnONPs.

The idea of decreasing the particle size of applied fertilizer is to deliver the “right dose of nutrients” in the “right place” and at the “right time.” Additionally, reducing the size of the particles leads to the increase in specific surface area of particles, thus the contact area of fertilizers with the plants will be increased resulting in the higher nutrient uptake by the plants in comparison to applied commercial fertilizers. The effect of Fe as nano and bulk Fe complex (Fe(III)-EDTA) applied at the same dose was studied under hydroponic conditions under Fe-deficient in tobacco cultivation (Bastani et al. 2018). It was found that the dry weight of the plant in 2 weeks after the application was about three times higher for nano Fe in comparison to bulk Fe. Elanchezhian et al. (2017) suggested that the application of FeNPs can significantly decrease the amount applied commercial Fe-fertilizers maintaining the proper growth and metabolism of crops.

Du et al. (2019) compared the effects of foliar ZnONPs and zinc sulfate at the same concentrations on the growth of wheat (*Triticum aestivum* L.). The highest Zn accumulation in grain was recorded with 100 mg dm⁻³ of ZnONPs which was about 29% higher when compared to applied 2000 ppm of zinc sulfate. Selenite, selenate, and Se nanoparticles (SeNPs) at doses 0.01–50 mg dm⁻³ were investigated for assessment of the phytotoxicity, accumulation, and transformation in garlic under hydroponic conditions. The highest Se content in roots was observed after application of selenite; however, the lowest translocation index of Se was observed in the case of application of SeNPs. The same results were observed for rice seedlings (Wang et al. 2020a). Tarafde et al. (2020) investigated the synthesis

Table 2 The effect of type of fertilizer, form, and dose of micronutrients application on biofortification with zinc, selenium, and iron. The enrichment factor (EF) was calculated as a ratio of results obtained from the most advantageous fertilization of the crops in relation to the control group

Reference	Plant	Form	Dose	Type of fertilizer/trial	Highlighted findings	EF
(Gomez-Coronado et al. 2016)	Wheat (<i>Triticum aestivum</i> L.)	Zn(II) ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$)	50 kg ha ⁻¹ 0.05% mix	Soil/foliar/soil + foliar/plot trial	DTPA-extractable Zn was not affected by the growing season. The application of a combination of soil and foliar fertilizers improved Zn concentration in grains greater than 20 mg kg ⁻¹ and improved the yield by about 180 kg ha ⁻¹	2.6 (grain)
(Liu et al. 2019)	Winter wheat (<i>Triticum aestivum</i> L.)	Zn(II) ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$)	0, 10, 25, 50, 100, 150 kg h ⁻¹	Soil/field trial	The biomass of wheat, Zn concentration in grains, and zinc accumulation in g ha ⁻¹ improved after Zn application, especially in the second year of the experiment. Significantly increased roots development and promoted the translocation of Zn from roots to grains at Zn treatment in dose ≤ 11.4 . Zn availability was higher in the soil layer 0–10 cm, where wheat roots were mainly distributed	1.09 (grain)
(Liu et al. 2017)	Wheat (<i>Triticum aestivum</i> L.)	Zn(II) ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$)	0, 10, 25, 50, 100, 150 kg h ⁻¹	Soil/pot/field trial	Over the 3 years of the experiment, Zn application to the soil significantly increased the wheat yield which was correlated with an increase in the numbers of spikes m ⁻² and grain spike ⁻¹ . Zn concentration of 29.4 mg kg ⁻¹ in shoots at anthesis and a soil DTPA-Zn concentration of 1.98 mg kg ⁻¹ were required to obtain high yields	N/A

Table 2 (continued)

Reference	Plant	Form	Dose	Type of fertilizer/trial	Highlighted findings	EF
(Sago et al. 2018)	Lettuce (<i>Lactuca sativa</i> L.)	Zn(II)	0.001, 0.1, 0.15, 0.3, 0.45 mM	Hydroponic	The concentration of Zn ≥ 0.15 mM significantly decreased fresh and dry weights. Higher wind speed and root zone temperature stimulated an increase of Zn concentration in leaves	N/A
(Haider et al. 2018b)	Mungbean (<i>Vigna radiata</i> L.)	Zn(II) ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$)	0, 2.5, 5.0, 7.5, 10 kg ha ⁻¹	Soil/pot trial	Zn application at 10 mg kg ⁻¹ soil significantly increased plant height, chlorophyll content, number of vegetative branches of plant ⁻¹ , pod length, and number of pods plant ⁻¹	1.64 (grain)
(Longchamp et al. 2015)	Corn (<i>Zea mays</i> L.)	Se(IV) (Na_2SeO_3) Se(VI) (Na_2SeO_4)	12 μM Se dm ⁻³	Hydroponic	Selenite application improved Se accumulation in roots and grains of corn; however, the total content of accumulated Se was the highest for selenate application. There were no statistical differences in grain Se content calculated per plant between the applied two forms of Se	N/A
(de Almeida et al. 2020)	Lettuce (<i>Lactuca sativa</i> L.)	Zn(II) ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$)	0, 5, 10, 20, 30 mg kg ⁻¹	Soil/pot trial	The highest content of Zn (781.3 μg plant ⁻¹) was accumulated in the leaves "Grand Rapids" genotype cultivated on Red-Yellow Latosol containing 73% of sand	4.4 (leaf)

Table 2 (continued)

Reference	Plant	Form	Dose	Type of fertilizer/trial	Highlighted findings	EF
(Niyigaba et al. 2019)	Wheat (<i>Triticum aestivum</i> L.)	Zn(II) + Fe(II)	0.26–3.0 kg Zn ha ⁻¹ + 0.22–2.6 kg Fe ha ⁻¹	Foliar/plot trial	Application of 80% Zn and 20% Fe at a dose of 5.5 kg ha ⁻¹ was the best combination for increasing crude protein of whole wheat grain. In terms of Zn and Fe accumulation in grains, the application of 60% Zn and 40% Fe showed the best results	1.64 (Zn grain) 1.10 (Fe grain)
(Sabatino et al. 2019)	Curly endive (<i>Cichorium endivia</i> L., var. crispum Hegl)	Se(VI) (Na ₂ SeO ₄)	0, 0.1, 2.0, 4.0, 8.0 µM dm ⁻³	Foliar vs fertigation/hydroponic	With increasing Se concentration, Se accumulation increased for both types of fertilization, foliar application, and fertigation. The highest head fresh weight was obtained for fertigation at 4.0 µM dm ⁻³	24.80 (shoot)
(Lara et al. 2019)	Wheat (<i>Triticum aestivum</i> L.)	Se(VI) (Na ₂ SeO ₄)	0, 12, 21, 38, 68, 120 g ha ⁻¹	Foliar/plot trial	The application of Se in a dose of 21 g ha ⁻¹ is the best strategy for improving yield and physiological benefits	3.92 (grain)

Table 2 (continued)

Reference	Plant	Form	Dose	Type of fertilizer/trial	Highlighted findings	EF
(Deng et al. 2017)	Rice (<i>Oryza sativa</i> L.)	Se(IV) (Na_2SeO_3) Se(VI) (Na_2SeO_4)	75 g ha ⁻¹	Foliar/field trial	No significant difference was found between late tillering and full heading stage treatments in terms of grain yield and total biomass. The 3.5 times higher Se grain concentration was obtained for selenate applied at the full heading stage in comparison to Se applied at the late tillering stage. It was found that the Se concentration in the husks became significantly higher than that in the brown rice upon a delay of the spraying stage	N/A
(Yin et al. 2019)	Rice (<i>Oryza sativa</i> L.)	Se(-II), MeSeCys + Se(-II), Se(IV) (Na_2SeO_3) Se(VI) (Na_2SeO_4)	400 µg 790 µg Se in total	Root irrigation or foliage dressing/hydroponic trial Foliar and soil/pot trail	About 73% of Se was accumulated in leaves of rice in form of Se-amino-acid after Se(-II) root irrigation	N/A
(Di Gioia et al. 2019)	Arugula (<i>Eruca sativa</i> (Mill.)), red cabbage (<i>Brassica Brassica oleracea</i> L.) red mustard (<i>Brassica juncea</i> L.) microgreens	Zn ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$) vs Fe ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$)	0, 5, 10, 20 mg dm ⁻³ 0, 10, 20, 40 mg dm ⁻³	Fertigation	The highest Fe level was found in red cabbage; however, the most effective accumulator for Zn at the concentration of 10 mg dm ⁻³ was red mustard. For the highest level of Zn and Fe, their content in shoots reached the highest toxicity levels that could be potentially toxic for consumers and were certainly toxic for the plants	3 (Zn-red mustard) 4 (Fe-red cabbage)

Table 2 (continued)

Reference	Plant	Form	Dose	Type of fertilizer/trial	Highlighted findings	EF
(da Silva et al. 2020)	Radish (<i>Raphanus sativus</i> L.)	Se(IV) (Na_2SeO_3) Se(VI) (Na_2SeO_4)	1.2 mg kg ⁻¹ 50 μM dm ⁻³	Soil or foliar/pot trial	Applied Se in form of Se(VI) to the soil gave higher Se concentration in roots in comparison to other treatments. The Se applied in selenate form was mostly transported to the shoots	N/A
(Cecílio Filho et al. 2015)	Chicory (<i>Cichorium intybus</i> L.)	Fe(II)	0.9, 2.7, 8.3, 25 mg dm ⁻³	Hydroponic	The application of Fe in the concentration above 8.3 mg Fe dm ⁻³ caused the decreasing plant weight, yield, and number of leaves	N/A
(Puccinelli et al. 2017)	Basil (<i>Ocimum basilicum</i> L.)	Se(VI) (Na_2SeO_4)	0, 4, 8, 12 mg Se dm ⁻³	Hydroponic	The applied Se even at a concentration of 12 mg dm ⁻³ did not affect the biomass production of basil plants. The highest Se was accumulated in leaves. With increasing, the Se content, the translocation factor increased	592.27 (leaf)
(Hawrylak-Nowak et al. 2015)	Cucumber (<i>Cucumis sativus</i> L.)	Se(IV) (Na_2SeO_3) Se(VI) (Na_2SeO_4)	2, 4, 6, 10, 20, 30, 40, 60 μM Se dm ⁻³ 2, 4, 6, 10, 20, 30, 40, 60, 80 μM Se dm ⁻³	Hydroponic	The biomass of roots and shoots significantly decreased at the highest concentration of selenate and selenite. Selenite application at a concentration above 10 μM Se dm ⁻³ has a more negative effect on the concentration of photosynthetic pigments in comparison to selenate	1.45 (selenate-shoot)

Table 3 The effect of biofertilizers on biofortification with zinc, selenium, and iron. The enrichment factor (EF) was calculated as a ratio of results obtained from the most advantageous fertilization of the crops in relation to the control group

Reference	Plant	Fertilizer	Micronutrient form and concentration	Type of trial	Highlighted findings	EF
(Padash et al. 2016)	Lettuce (<i>Lactuca sativa</i> L.)	Zn + <i>Piriformospora indica</i>	0, 2.5, 5, 10 mg dm ⁻³ (ZnSO ₄ 7H ₂ O)	Pot trial	An increase in Zn concentration resulted in increased growth parameters, leaf numbers, Zn concentration, total chlorophyll, and Mn content in lettuce leaves. Decreased level of Fe. The Cu concentration did not change	7.62 (leaf)
(Abaid-Ullah et al. 2015)	Wheat (<i>Triticum aestivum</i> L.)	Zn + <i>Serratia liquefaciens</i> FA-2, <i>S. marcescens</i> FA-3, and <i>Bacillus thuringiensis</i> FA-4	0.1% of the insoluble different zinc compounds (ZnO, Zn ₃ (PO ₄) ₂ , ZnS, ZnCO ₃)	Plot trial	Zn solubilizer consortium (FA-2, FA-3, and FA-4) resulted in an increased grain spike, yield, biomass, and Zn concentration. Different responses depending on genotype	1.43 (grain <i>S. liquefaciens</i> FA-2)
(Tran et al. 2019)	Wheat (<i>Triticum aestivum</i> L.)	Zn + <i>Rhizophagus irregularis</i> WEFVAM10	0, 5, 25, 50, 150 mg kg ⁻¹ (ZnSO ₄ 7H ₂ O)	Pot trial	Increased Zn grain concentration only for Zn application at 150 mg Zn kg ⁻¹ soil. Decreased Fe, P, and increased phytic acid concentration	5.3 (grain)
(Patel et al. 2018)	Mungbean (<i>Vigna radiata</i> L.)	Fe + <i>Pantoea dispersa</i> MPJ9 and <i>Pseudomonas putida</i> MPJ6	1, 5, 10, 15, 20, 25, 50, 100 µM (FeCl ₃ ·6H ₂ O)	Pot trial	Higher Fe concentration and increased fruit, shoot, and root weight protein and carbohydrate content	4.95
(Yasin et al. 2015a)	Wheat (<i>Triticum aestivum</i> L.)	Se + <i>Bacillus pichinotyi</i> -YAM2	3 mg Se kg ⁻¹ (double dose of Na ₂ SeO ₄)	Pot trial	Increased dry weight, shoot length, and acid phosphatase activity, and decrease of protein content after inoculation with Se. Enhanced Se and Fe concentration in stems and kernels	2.75 (grain Se) 2.4 (grain Fe)
(Yasin et al. 2015b)	Wheat (<i>Triticum aestivum</i> L.)	Se + <i>Bacillus cereus</i> -YAP6, <i>Bacillus licheniformis</i> -YAP7	3 mg Se kg ⁻¹ (double dose of Na ₂ SeO ₄)	Pot trial	Increased seed weight, number of seeds per plant, Se, S, Ca, and Fe stem, and kernels concentration	2.83 (seed- <i>Bacillus cereus</i> YAP6)

Table 3 (continued)

Reference	Plant	Fertilizer	Micronutrient form and concentration	Type of trial	Highlighted findings	EF
(Golubkina et al. 2019)	Shallot (<i>Allium cepa</i> L.)	Se + Fungus- <i>Rhizophagus intradices</i> (with low content of <i>Trichoderma harzianum</i> and <i>Bacillus subtilis</i>)	Na ₂ SeO ₄ and selenocysteine at 63 mg m ⁻²	Plot trial	Increased dry matter, shallot bulb yield and weight, protein, and Se content bulb. Better results were obtained for inoculation fungus with selenocysteine (SeCys)	36.71 (bulb)
(Golubkina et al. 2020)	Chickpea (<i>Cicer arietinum</i> L.)	Se + Fungus- <i>Rhizophagus intradices</i> (with low content of <i>Trichoderma harzianum</i> and <i>Bacillus subtilis</i>)	150 mg m ⁻² , by 50 mg dm ⁻³ 0.26 mM solution of Na ₂ SeO ₄ , 300 mg m ⁻² , by 100 mg dm ⁻³ 0.6 mM solution of potassium iodide	Plot trial	Increased dry weight, seed yield, number of seeds per plant, antioxidant activity, protein, Zn, Fe, Cu, and Mn content	39.35 (seed)

of the formulated slow-release fertilizers by incorporating hydroxyapatite, urea, and NPs of Cu, Fe, and Zn (HNF) and have compared their effect and commercial fertilizer on the accumulation of Zn, Fe and Cu in *Abelmoschus esculentus* cultivation. Application of HNF about 16, 3, and 146 times improved total uptake of Cu, Fe, and Zn, respectively, in comparison to commercial fertilizer.

The effect of NPs on biofortification with zinc, selenium, and iron is shown in Table 4.

3 The Beneficial Effect of Se, Zn, and Fe on their Content and Nutritional Quality of Crops

Biofortification with Zn, Se, and Fe not only increases microelement content in the edible parts of crops, yield, and morphological parameters of crops but also have a beneficial impact on other nutritional parameters of crops like, i.e., increase of proteins, amino acids, phenolic acids, chlorophyll, carotenoids, and essential oil content. However, it is worth noting that success in crops enrichment by micro-nutrients can be achieved only when there are no negative symptoms on crops like, i.e., biomass reduction. Zn, Se, and Fe fertilizers have an impact on the increase of the contentment of antioxidant compounds. Understanding stress physiology in plant growth can allow for the controlled synthesis of antioxidant compounds which are very valuable food compounds. For example, phenolic compounds are believed to scavenge and/or inhibit the production of ROS in the human body, thus preventing a critical step at the onset of carcinogenesis. The increase of antioxidant properties in plants can be caused by (i) the synthesis of not only phenolic compounds but also by other secondary metabolites exhibit antioxidant properties, (ii) the effect of microelements on the redox metabolism of glutathione (GSH) and enzymes involved in GSH metabolism, and (iii) the direct antioxidant effect microelement and its organic metabolites (Skrypnik et al. 2019).

It was found that application of Se to the nutrient solution at a dose of 12 mg dm⁻³ at the first and second cut has a significant effect on increased total phenol content in leaves basil. There were no significant differences in antioxidant capacity, rosmarinic acid content, total chlorophyll content, and leaf biomass between Se application and control (Puccinelli et al. 2020). The same results were obtained by Skrypnik et al. (2019) but for lower Se concentration (up to 0.78 mg dm⁻³). Contrary, Edelstein et al. (2016) noted that in order to avoid the reduction of the yield of basil, Se concentration in nutrient solution should be lower than 0.25 mg dm⁻³. Differences in Se accumulation could be different in varieties of basil. Two varieties of basil were tested on essential oil and Se content after foliar Se fertilization.

The “Red Rubin” variety distinguished higher fresh phyto-mass yield and about two times higher Se content in leaves compared to the “Dark Green” variety; however, the content of essential oil was higher in “Dark Green” variety (Mezeyova and Hegedusova 2016). In the study conducted by Barátová et al. (2015), the variety of “Red Opal” had greater polyphenol content at first and second cut than “Dark Green.”

Two varieties of lettuce were studied under hydroponic conditions with increasing Fe concentration. The accumulation of Fe of both varieties increased with increasing dose of Fe; however, the variety of “Red Salanova” performed the higher phenolic acids as well as phenolic content compared to “Green Salanova.” Additionally, the significantly increased carotenoid content was observed only for the red lettuce variety. It is worth noting that only Fe applied at the concentrations at 0.5 mmol dm^{-3} did not decrease the fresh and dry biomass of lettuce per plant (Giordano et al. 2019). Contrary, the application of Zn at the concentration of $0.45 \text{ mmol dm}^{-3}$ significantly decreased these parameters in the red variety of lettuce (Sago et al. 2018).

Out of all types of crops, those enriched with sprouted seeds and microgreens deserve particular attention as they are a natural source of cancer preventive compounds (Park et al. 2015; Turner et al. 2020). Their biofortification gives the possibility to self-produce nutrient-dense plants in a very short time with the use of simple soilless systems. Se in the form of selenate at concentration 4 and 8 mg dm^{-3} significantly improved germination index, Se content, antioxidant capacity, and dry/fresh weight of microgreens of basil (Puccinelli et al. 2019a, b). The concentration of Se in microgreens was about 2.2 times higher than in leaves of maturity basil. This suggests that microgreens have a higher nutritional value and greater health benefits compared to mature leafy vegetables. The increased antioxidant capacity detected in the Se-enriched microgreens is in agreement with the results obtained in *P. oleracea* (Puccinelli et al. 2021a) and *Ocimum basilicum* L. *Coriandrum sativum* L., and *Allium fistulosum* L. (Newman et al. 2021). The application of selenate and selenite at $100 \text{ } \mu\text{M dm}^{-3}$ was tested on three varieties of broccoli. The results showed that the application of selenate improved anthocyanin and ascorbic acid content in tested broccoli varieties, whereas the selenite was more effective in the accumulation of flavonoid content. There were no significant differences between the form of applied Se for total phenolic content; however, in both cases, the total phenolic content was lower than control (Tian et al. 2016). In the study conducted by Vicas et al. (2019), application of SeNPs even higher concentrations did not affect changes in the total phenol content. On the other hand, it was found that both the soaking and spraying pea seeds with Zn significantly increased the total phenolic content up to Zn application at 40 mg dm^{-3} (Lingyun et al. 2016).

The effect of biofortification with Zn, Se, and Fe on plant metabolism is provided in Table 5.

4 The Influence of Biofortification with Zn, Se, and Fe on the Defense of Plants Against Abiotic Stress

Abiotic stresses such as salt, high/low temperature, heavy metal, and drought cause, i.e., overproduction of reactive oxygen species (ROS) and inducement of oxidative stress in plants. It was evidenced that biofortification with Zn, Se, and Fe using different types and forms of fertilizer can reduce the damage caused by oxidative stress by an increase of ROS-scavenging enzymes like (superoxide dismutase (SOD), ascorbate peroxidase (APX), catalase (CAT), glutathione peroxidase (GPX), monodehydroascorbate reductase (MDHAR), dehydroascorbate reductase (DHAR), glutathione reductase (GR), glutathione S-transferase (GST), and peroxiredoxin (PRX) content in different sites of plant cells (Amira et al. 2015; Noreen et al. 2020). The application of microelements also enhanced the content of non-enzymatic antioxidants such as GSH, ASA, carotenoids, and proline which are also crucial for the maintenance of ROS homeostasis in the plant. In addition, to maintain the balance of ROS in plants, the application of micronutrients significantly decreased the level of heavy metals in plant tissues, and improved morphological growth parameters and Zn, Se, and Fe concentration in edible parts of crops.

Of all toxic heavy metals, the most frequently studied was the alleviation of the Cd stress which is recognized as one of the most hazardous environmental contaminants. Rizwan et al. (2019) found that soaking wheat seeds with ZnNPs and FeNPs significantly decreased wheat grain Cd concentration (about 82%). Similar results were obtained for soil and foliar application of FeONPs (Hussain et al. 2019). Wheat seeds, with different concentrations of intrinsic Zn, were planted in artificially Cd contaminated soil. The lowest grain Cd concentration was observed for crops that grow from seeds with high intrinsic Zn cultivated on soil enrichment with Zn and biochar.

It has been estimated that the one billion hectares of arid and semi-arid areas of the world remain barren due to salinity or water scarcity (Sahab et al. 2021). The application of Se can significantly mitigate the toxic influence of salt stress. For example, Se application at a low concentration of $5\text{--}10 \text{ mg dm}^{-3}$ under salinity conditions significantly increased the antioxidant enzymes activities, the total phenol and flavonoid content, and the enhancement of the K/Na ratio in grapes (Karimi et al. 2020). The application of SeNPs at the concentration of 10 mg dm^{-3} also increased about 1.85 times enzymatic antioxidant content (APX, GPX, CAT, and SOD) in tomato fruits cultivated on

Table 4 The effect of nanofertilizers on biofortification with zinc, selenium, and iron. The enrichment factor (EF) was calculated as a ratio of results obtained from the most advantageous fertilization of the crops in relation to the control group

Reference	Plant	Micronutrient form and concentration	Concentration	Type of fertilizer/trial	Highlighted findings	EF
(Tarafder et al. 2020)	Okra (<i>Abelmoschus esculentus</i>)	Urea-modified hydroxyapatite mixed with Cu, Fe and Zn (HNF) Commercial fertilizer	50 mg week ⁻¹ 5 g week ⁻¹	Soil/pot trial	The application of HNP increased the water retention capacity of soil and uptake of Fe and Zn nutrients in comparison to commercial fertilizer. The release of Fe ²⁺ and Zn ²⁺ rapidly increased after 7 days from application	2.86 (fruit-Fe) 146.54 (fruit-Zn)
(Yahyaoui et al. 2017)	Wheat (<i>Triticum aestivum</i> L.)	ZnONPs	0–2000 mg dm ⁻³	Germination	The application of 10 mg dm ⁻³ of ZnONPs have no significant effect on relative length of roots and leaves, all of doses applied ZnONPs have significant effect on catalase, ascorbate peroxidase activities, and malondialdehyde and hydrogen peroxide in roots and leaves	N/A
(Du et al. 2019)	Wheat (<i>Triticum aestivum</i> L.)	ZnONPs vs Zn(II) sulfate form	0–1000 mg dm ⁻³	Soil/pot trial	Application of ZnONPs at 50 mg dm ⁻³ have significant effect on Zn content in grain and harvest index. The analysis XRD did not present Zn as nano ZnO form in a different part of plant	3.3. (grain)

Table 4 (continued)

Reference	Plant	Micronutrient form and concentration	Concentration	Type of fertilizer/trial	Highlighted findings	EF
(Subbaiah et al. 2016)	Corn (<i>Zea mays</i> L.)	ZnONPs vs Zn(II) in sulfate form	50, 100, 200, 400, 600, 800, 1000, 1500, 2000 mg dm ⁻³	Germination, foliar/pot trial	The highest germination percentage (80%) and seedling germination vigor index (1923.2) was obtained for ZnONPs at 1500 ppm. Application of 400 mg dm ⁻³ of ZnONPs has the best effect on grain yield in comparison to control and bulk ZnSO ₄	1.37 (grain)
(Deshpande et al. 2017)	Wheat (<i>Triticum aestivum</i> L.)	Zn-chitosan NPs (Zn-CNP)	~ 25 mL, Zn content ~ 20 mg g ⁻¹	Foliar/pot trial	The Zn-CNP improved about 1.25 times Zn concentration in a grain of both varieties of wheat. It was found that high pH affected the formation of the nanoparticles and agglomerated particles were formed	1.25 (grain)

Table 4 (continued)

Reference	Plant	Micronutrient form and concentration	Concentration	Type of fertilizer/trial	Highlighted findings	EF
(Li et al. 2020b)	Garlic (<i>Allium sativum</i> L.)	SeNPs vs Se(IV) vs Se(VI)	0, 0.01, 0.1, 1, 10, 50 mg dm ⁻³	Hydroponic	SeNPs exhibited the lowest phytotoxicity and were stable in water but prone to convert to i.e. MeSeCys upon uptake by roots (above 60% of the total Se). SeNPs and Se(IV) were mainly accumulated in roots, while Se(VI) was easily transported to shoots. The lowest translocation factor was observed for SeNP	11 (bulb)
(Hussein et al. 2019)	Groundnut (<i>Arachis hypogaea</i> L.)	SeNPs	0, 20, 40 mg dm ⁻³	Foliar/pot trial	With increasing of the SeNPs, the number of pods, pods weight, seed weight, number of seeds, oil yield increased	N/A
(Li et al. 2016)	Corn (<i>Zea mays</i> L.)	γ-Fe ₂ O ₃ NPs	0, 20, 50, 100 mg dm ⁻³	Germination/hydroponic	There were no significant differences in germination between treatments. At application of γ-Fe ₂ O ₃ NPs at 20 mg dm ⁻³ , the highest vigor index and root length were observed. Application of the significantly decreased value of the translocation index	N/A

salinity (Morales-Espinoza et al. 2019). The minimalized consequence of salt stress in plants was also mitigated by a combination of Zn with ascorbic acid in barley (Noreen et al. 2020).

It is worth noting that numerous studies on the impact of micronutrients on alleviation of negative effects of abiotic stress have been performed under laboratory conditions, and only a few were conducted in natural, field conditions (Nawaz et al. 2017). Table 6 summarizes the influence of biofortification with Zn, Se, and Fe on the adaptation of plants under stress conditions.

5 Future Perspectives and Strategies

Agronomic biofortification is the most promising way to successfully alleviate micronutrient malnutrition by increasing the mineral content in the crops and simultaneously enhancing their bioavailability by reducing antinutritional compounds and/or enhancing the concentration of mineral absorption promoters. Zn, Se, and Fe biofortification efforts should consider the concentration and species of micronutrients accumulated in the plant in relation to the effects that such micronutrients enrichment could exert on the production of health-beneficial and/or stress-defense compounds. Additionally, the balance between the production and nutrient requirements of Zn, Fe, and Se should be included in considerations of sustainable intensification.

Based on the collected data there is still a lot of missing information that should be considered when planning future research:

- 1 most of the research into biofortification with micronutrients was conducted in laboratory conditions under strictly controlled environmental factors and it is important to verify those results under a wide variety of environmental conditions;
- 2 there is a lack of information in the collected data about the form of application of fertilizer on the transfer of microelements, e.g., granules vs. liquid form vs. encapsulated fertilizers. What is also missing is information around the influence of soil properties on the release of micronutrients during long-term application;
- 3 in many studies, there is also a lack of basic characteristics of soils, like pH, the content of organic matter, salinity, and moisture which are very important factors regulating the form and concentration of micronutrients in the soil;
- 4 the total micronutrient content in plants is not always an appropriate indicator of its useful nutritional quality as the human body can absorb only a particular form and dose of micronutrients and only a few studies covered the determination of the form of compounds accumulated micronutrients;
- 5 further studies are required with more species and/or cultivars of the same species under variable growing conditions to define the best practice for Zn, Se, and Fe agronomic biofortification;
- 6 further research is required to estimate Zn, Se, and Fe bioavailability in biofortified microgreens, sprouts, and baby greens;
- 7 some papers proved that fertilization with more than one micronutrient gives better effects than applied alone. However, it is worth mentioning that is needed to reach fine-tune doses to obtain an adequate accumulation of micronutrients in edible parts of crops without limiting growth and quality parameters. More studies are required to gain an understanding of the antagonistic and competitive effects of nutrient elements on plant uptake of Se, Zn, and Fe;
- 8 to achieve sustainable agricultural productivity, growers should switch from a high input-based production system to the cultivation of soil–plant–microbiom interaction-based systems. More work should be focused on:
 - studying biological inoculants in the agriculture field under changing climatic conditions and competition by indigenous microorganisms
 - better understanding the effect of plant beneficial rhizobacteria on the effective utilization of these microbes in mitigating various abiotic stresses
 - studying promotion of plant growth with a combination of microorganism with a mix of micronutrients at different concentrations;
- 9) the increasing commercial use of NPs may result in unintended exposure to flora and fauna of the environment. Key aspects that influence toxicity in plants are the following: the concentration of NPs, particle size, surface area, stability, physicochemical properties, plant species, plant age/phenological stage, the medium of exposure, and dilution agent. The future research should be conducted utilizing the processes of translocation and accumulation of micronutrient NPs in crops. This area of research has not been studied adequately and much more studies have been performed up to the germination stage, providing only limited information. Due to the finite term of existence of NPs, there is a need to perform research under the stability of NPs in time. Additionally, from the environmental protection point of view, strict dosage and distribution control of NPs is a very important issue for ensuring that the application of NPs poses no potential risk for plants, animals, and humans. The application of NPs is a very promising way in crops

Table 5 The effect of biofortification with Zn, Se, and Fe on plant metabolism. The enrichment factor (EF) was calculated as a ratio of results obtained from the most advantageous fertilization of the crops in relation to the control group

Reference	Plant	Micronutrient/type of fertilizer	Highlighted findings	EF
(Puccinelli et al. 2020)	Basil (<i>Ocimum basilicum</i> L.)	Se/hydroponic	The antioxidant capacity, the total phenol, and the rosmarinic acid content at harvest, the total chlorophyll content increased with increasing dose of selenate. Application of Se did not affect the leaf concentration of carotenoids. It was found that after 5 days of storage, the ethylene concentration was the lowest for application of 4 mg Se dm ⁻³	more than 1200 (leaf)
(Skrypnik et al. 2019)	Basil (<i>Ocimum basilicum</i> L.)	Se/foliar/hydroponic	A significant increase of essential oils was obtained for application of Se at a concentration of 2 and 5 µM by the addition of Se to the nutrient solution and by foliar application, respectively. All of the treatments significantly increased the antioxidant activity of basil leaves extracts in comparison to control	more than 1400 (leaf)
(Asif et al. 2017)	Basil (<i>Ocimum basilicum</i> L.)	Zn/irrigation	The highest total phenolics, total flavonols, antioxidant content, and also the highest rate of inhibition in the linoleic acid system were achieved at 0.095 Zn mg dm ⁻³ . Essential oil originating from biofortified plants exhibits about 20% higher antifungal activity in comparison to control	N/A
(Tian et al. 2016)	Broccoli (<i>Brassica oleracea</i> L. sprouts)	Se/spraying	Application of selenate significantly increased the ascorbic acid in FL60 and WX90 varieties, while selenite increased flavonoid and sulforaphane content and myrosinase activity	8.5 (all plant)
(Vicas et al. 2019)	Broccoli (<i>Brassica oleracea</i> L.) sprouts	SeNPs/spraying	Spraying SeNPs increased chlorophyll a and glucosinolate content. No differences in phenolic acids and carotene content were observed. Only 100 mg dm ⁻³ of SeNPs caused increased antioxidant capacity	2.44 (root)
(Newman et al. 2021)	Basil (<i>Ocimum basilicum</i> L.) Cilantro (<i>Coriandrum sativum</i> L.) Scallions (<i>Allium fistulosum</i> L.) microgreens	Se/hydroponic	The highest Se concentration was found in scallion, whereas the highest total phenol content was accumulated in basil. The application of 10 mg dm ⁻³ of Se was toxic for microgreens, especially for basil and cilantro	507 (scallion)

Table 5 (continued)

Reference	Plant	Micronutrient/type of fertilizer	Highlighted findings	EF
(Schiavon et al. 2016)	Radish (<i>Raphanus sativus</i> L.)	Se/foliar/pot trial or hydroponic	At the concentration of 20 mg dm ⁻³ the level of glucoraphanin, glucoraphasatin glucobrassicin, and neoglucobrassicin in roots significantly increased in pot experiment; however, there were no significant differences under hydroponic cultivation. There were no significant differences in total amino acids between treatments but in case of hydroponic conditions their content decreased about 25%	271.59 (root-pot trial)
(Acqua et al. 2019)	Rocket (<i>E. sativa</i> and <i>D. tenuifolia</i>)	Se/hydroponic	The content of amino acids significantly decreased in all treatments in <i>E. sativa</i> and significantly increased in <i>D. tenuifolia</i> above 20 µM of Se. Phenol content in leaves significantly decreased in all treatments in <i>D. tenuifolia</i> but except for the highest level of Se in the nutrient solution, there were no significant differences in <i>E. sativa</i>	N/A
(Puccinelli et al. 2021a, b)	Common sorrel (<i>Rumex acetosa</i> L.) Buckhorn plantain (<i>Plantago coronopus</i> L.) Common purslane (<i>Portulaca oleracea</i> L.)	Se/nutrient solution	The highest accumulation of Se, the total chlorophyll, and flavonoid content was observed in Buckhorn plantain. The application of Se increased by about 3%, 26%, and 13% the total phenol content in Common sorrel, Buckhorn plantain, Common purslane, respectively	448 (spraying) 357 (soaking)
(Lingyun et al. 2016)	(<i>Pisum sativum</i> L.) sprouts	Zn/soaking vs spraying	With fertilization by Zn the chlorophyll, content, soluble sugar amino acids: proline, threonine, valine, methionine, isoleucine, leucine, tryptophane, and phenylalanine and APX, GR, T-AOC, and AsA activities increased	
(Bachiega et al. 2016)	Broccoli (<i>Brassica oleracea</i> L.) sprouts and microgreens	Se/soaking	Se application increased the phenolic compound content by 25% and 6% in sprouts and microgreens, respectively. It also had a significant effect on the antioxidant activity. Differences were found between antioxidant activity measured by three different methods (DPPH, ABTS, FRAP)	N/A
(Li et al. 2020a)	Pepper (<i>Capsicum annuum</i> L.)	SeNPs vs Se(IV)/foliar	Application of SeNPs at dose 20 significantly increased chlorophyll, soluble sugar, ascorbic acid, total phenols, and flavonoid content in pepper fruits. SeNP fertilizers promoted the expression of phytohormone synthesis genes	N/A

Table 5 (continued)

Reference	Plant	Micronutrient/type of fertilizer	Highlighted findings	EF
(Giordano et al. 2019)	Lettuce (<i>Lactuca sativa</i> L.)	Fe/nutrient solution	The anthocyanin content significantly increased at 0.5 and 2.0 mM dm ⁻³ of Fe in red Salanova lettuce. The red variety of lettuce had about 8, 1.6, and 12.8 higher chlorogenic, chlorogenic, and caffeoyl meso tartaric acid content, respectively, in comparison to green Salanova. Only the application of 0.5 mM dm ⁻³ of Fe significantly increased the total phenolic acid content in red Salanova	more than 6066 (leaf)
(Park et al. 2015)	Alfalfa (<i>Medicago sativa</i> L.), broccoli (<i>Brassica oleracea</i> L.), radish (<i>Raphanus sativus</i> L.) sprouts	Fe/soaking	The best soaking times for alfalfa, broccoli, and radish seeds were determined to be 7 h, 8 h, and 5 h, respectively. Soaking seeds with iron chelates enhanced the iron concentration of sprouts, especially in alfalfa sprouts. Significant differences were observed between treatment and control in terms of the total phenolic content only for alfalfa	1.63 (alfalfa)

fertilization; however, the focus should be on the greener approach for the synthesis of metal oxide nanoparticles, which would, to some extent, help in limiting toxicity towards the environment;

- 10) it is quite easy to evaluate the responses of single species or a few plant species to Se, Zn, or Fe under the effect of one single stress in the laboratory. There are many factors in field conditions that are responsible for plant stress, the reaction of plants can differ in comparison to results obtained on a laboratory scale, and it is important to perform more experiments in field conditions. One of the main future challenges is to better recognize Se-, Zn-, and Fe-plant interactions under abiotic stress to reveal the beneficial role of these micronutrients. Furthermore, studies with full life cycles of plants are also needed, especially to better understand the impacts of NPs on heavy metal accumulation by plants grown in realistic contaminated soils.

6 Conclusion

Agronomic biofortification of staple and non-staple crops with Zn, Se, and Fe using mineral and organic fertilizers has an exceptional potential for a fight with hidden hunger worldwide. The review is focused on the state-of-art application of Zn, Se, and Fe fertilizers including the selection of the type of fertilizers (including nanofertilizers and biofertilizers), type and dose of applied micronutrients, and their accumulation by selected crops. Besides an insight into the application of Zn, Se, and Fe in terms of increasing the nutritional value of crops, the review also presents positive influence of micronutrients on alleviating the damage caused by abiotic stress.

The success of agronomic biofortification depends on many important factors and, although numerous papers have been published regarding Zn, Se, and Fe fertilization and the effect of many factors on the effectiveness of agronomic biofortification, the understanding of this topic is still unclear. Based on collected literature, it could be concluded that more research should be performed concerning: field experiments with variable conditions and full life cycles of plants, the impact of soil properties on the release of micronutrients during long-term application, the determination of the form of compounds accumulated micronutrients in edible parts of crops, the reaction of species and/or cultivars of the same species on Zn, Se, and Fe fertilization and different ways of application fertilizer, an antagonistic and competitive effects of different factors on plant uptake of Se, Zn, and Fe, impact of biofertilizers and nanofertilizers on environment and accumulation in edible parts of crops, the impact of Zn, Se, and Fe on heavy metal

Table 6 Effect of biofortification with zinc, selenium, and iron on the adaptation of plants under stress conditions. The enrichment factor (EF) was calculated as a ratio of results obtained from the most advantageous fertilization of the crops in relation to the control group

Reference	Plant	Fertilizer/stress	Type of fertilizer/trial	Highlighted findings	EF
(Noreen et al. 2020)	Barley (<i>Hordeum vulgare</i> L.)	Zn + ascorbic acid/salt stress	Foliar/pot trial	Application of Zn + ascorbic acid increased about 2, 1.8, and 1.58 times the number of tillers per plant, spike length, and 100-grain weight, respectively, in barley cultivated on saline soil. It was observed to significantly decrease proline H_2O_2 and MDA contents in leaves. Additionally, applied fertilizer significantly increased the activity of SOD, POD, CAT, and APX in leaves	2.72 (leaf) 2.64 (root)
(Farooq et al. 2020)	Wheat (<i>Triticum aestivum</i> L.)	Zn + biochar/Cd stress	Soil/pot trial	Seeds with high intrinsic Zn combined with biochar increased superoxide dismutase and peroxidase activities, proline content, and grain Zn concentration with decreasing Cd content	1.2 (grain)
(Adrees et al. 2021)	Wheat (<i>Triticum aestivum</i> L.)	ZnONPs/Cd + water deficient	Foliar/pot trial	The best results were obtained for the application of 100 mg dm^{-3} ZnONPs. NPs minimized the electrolyte leakage, boosted up leaf chlorophyll a and b content and increased leaf superoxide dismutase and peroxidase activities, and decreased Cd concentrations in grain by 81%. Drought did not change the content of Zn in grains	2.4 (grain)
(Rizwan et al. 2019)	Wheat (<i>Triticum aestivum</i> L.)	ZnONPs FeONPs/Cd	Seed soaking/pot trial	The best results were obtained for the highest doses of ZnONPs and FeONPs. Primed seed with NPs influence an increase of superoxide dismutase and peroxidase activities, plant height, shoot and husk dry weight, chlorophyll and carotenoid content, and Zn/Fe concentration in grain under Cd stress	3.33 (grain Zn) 2.11 (grain Fe)

Table 6 (continued)

Reference	Plant	Fertilizer/stress	Type of fertilizer/trial	Highlighted findings	EF
(Elsheery et al. 2020)	Sugarcane (<i>Saccharum officinarum</i> L.)	ZnNPs/SeNPs/chilling stress	Foliar/field trial	During the cold front, foliar application of NPs maintained the higher maximum photochemical efficiency of PSII (F_v/F_m) and maximum photo-oxidizable P700 (P_m) compared to that of the NPs control. The moderately chilling tolerant [Guitang 49] seedlings treated with NPs have higher photosynthetic rate (P_N), stomatal conductance (gs), and carboxylation capacity (CE) values and positive correlations of these parameters with F_v/F_m	N/A
(Hussain et al. 2019)	Wheat (<i>Triticum aestivum</i> L.)	FeONPs/Cd stress	Foliar/soil/pot trial	A significant decrease of Cd content in shoots ($\pm$ 50%), roots ($\pm$ 46%), and grains ($\pm$ 80%) with increasing Fe concentration was observed for the application of 20 mg dm^{-3} FeNPs. There were no significant differences between the types of fertilization. The FeNP fertilization increased superoxide dismutase and peroxidase activities, dry weight of roots, shoots, grain, and husks, chlorophyll and carotenoid content, and photosynthetic and transpiration rate	2.85 (grain)

Table 6 (continued)

Reference	Plant	Fertilizer/stress	Type of fertilizer/trial	Highlighted findings	EF
(Niu et al. 2020)	Tea (<i>Camellia sinensis</i> L.)	Se/fluoride stress	Nutrient solution/hydroponic	Application of Se significantly decreased fluoride content in leaves and increased accumulation of F in roots. With an increase in Se concentration, the activities of SOD, POD, and CAT first increased, but then decreased at 1.0 Se mg dm ⁻³ . Application of Se significantly decreased MDA content in leaves	12.5 (leaf–highest F concentration)
(Huang et al. 2018)	Strawberry (<i>Fragaria × ananassa</i> Duch.)	Se/chilling stress	Foliar/pot trial	Application of Se decreased MDA and H ₂ O ₂ content and alleviated chlorophyll degradation under low-temperature stress. Additionally, an increase in the monodehydroascorbate reductase (MDHAR) was observed. MDHAR is a key enzyme in the defense against low-temperature stress	N/A
(Jiang et al. 2020)	Cucumber (<i>Cucumis sativus</i> L.)	Se/Cd	Foliar/hydroponic	The Cd concentration in fruit decreased with increasing Se level. However, the highest Se concentration (2 mg dm ⁻³) affected a decrease in the biomass of fruit in comparison to the lower treatments. The total phenol and flavonoid content significantly increased with increasing of Se concentration up to 10 mg dm ⁻³)	N/A

Table 6 (continued)

Reference	Plant	Fertilizer/stress	Type of fertilizer/trial	Highlighted findings	EF
(Karimi et al. 2020)	Grape (<i>Vitis vinifera</i> L.)	Se/Salt stress	Foliar/pot trial	Application of Se (selenate) at a concentration of 5 mg dm^{-3} improved plant weight (23%), leaf number (8%), leaf area (5%), the total chlorophyll content (24.5), and carotenoid content (66%) in comparison to the variant with salinity stress without Se application	17.51 (leaf)
(Shah et al. 2020)	Millet (<i>Setaria italica</i> L. and <i>P. miliaceum</i> L.)	Se/salt stress	Nutrient solution/hydroponic	Different responses on salt stress depended on a variety. Even a small dose of Se (50 mM) decreased the negative salt stress effect	N/A
(Morales-Espinoza et al. 2019)	Tomato (<i>Solanum lycopersicum</i> L.)	SeNPs/salt stress	Nutrient solution/pot trial	The application of SeNPs significantly increased the amount of both enzymatic and non-enzymatic compounds in the leaves and fruits of tomatoes. Best results were obtained for SeNPs at concentration 10 mg dm^{-3}	N/A
(Gudkov et al. 2020)	Radish (<i>Raphanus sativus</i> var. <i>sativus</i>) arugula (<i>Eruca sativa</i>) eggplant (<i>Solanum melongena</i>) tomato (<i>Solanum lycopersicum</i>) Cucum-ber (<i>Capsicum annuum</i>) chilli pepper (<i>Capsicum annuum</i>)	SeNPs/high-temperature	Soil/pot trial	Application of SeNPs at the concentration of $10 \text{ } \mu\text{g kg}^{-1}$ on the 30th day after the beginning of the plant growth (including 5-days hyperthermia of $40 \text{ }^{\circ}\text{C}$) significantly increased the leaf plate surface area in comparison to control in eggplant, cucumber, tomato, and chilli pepper. The leaf plate surface area tested plant significantly increased using SeNPs	N/A

Table 6 (continued)

Reference	Plant	Fertilizer/stress	Type of fertilizer/trial	Highlighted findings	EF
(Djanaguiraman et al. 2018)	Sorghum (<i>Sorghum bicolor</i> L.)	SeNPs/high-temperature stress	Foliar/pot trial	Application of SeNPs (10 mg dm^{-3}) in the optimum temperature did not significantly change the malondialdehyde content, chlorophyll index, thylakoid membrane damage, stomatal conductance, photosynthetic rate, superoxide radical content, hydrogen peroxide content, and cell membrane damage in comparison to control. Generally, all of the tested parameters significantly decreased under high-temperature conditions in comparison to control. Under high-temperature application of SeNPs significantly increased activity of SOD, GPX, CAT, and POX	N/A
(Sheikhalipour et al. 2021)	Bitter melon (<i>Momordica charantia</i> L. cv. Palee F1)	Chitosan–selenium nanoparticle (Cs–Se NPs)/salt stress	Foliar/pot trial	Application of 10 and 20 mg dm^{-3} of Cs–Se NPs significantly increased the total phenol, flavonoid, vitamin C, anthocyanin, total chlorophyll content, and antioxidant activity under salinity stress and decreased MDA and H_2O_2 content in leaves	N/A

accumulation by crops especially grown in realistic heavy metals levels in the soil.

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Declarations

Conflict of Interest The authors declare no competing interests.

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