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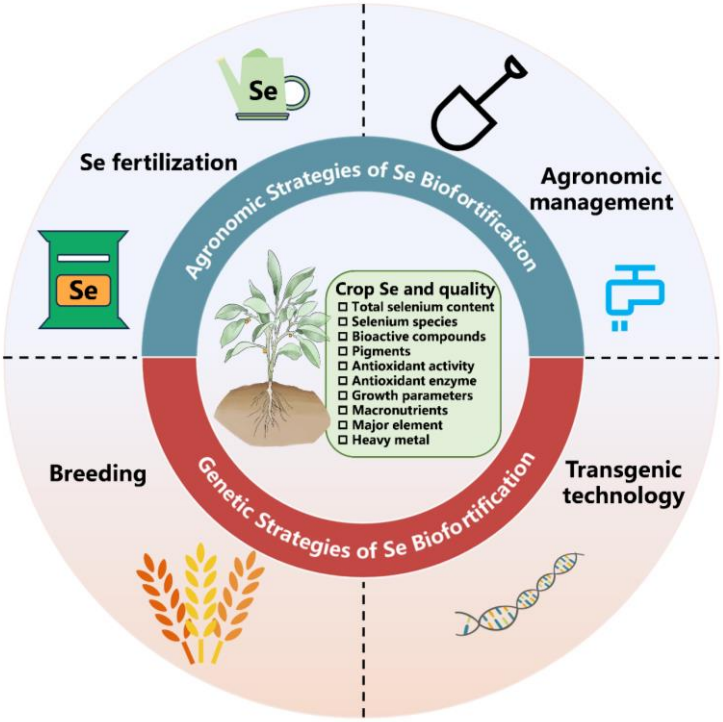
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Review

Progress in selenium biofortification and its effects on crop quality

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Abstract: Se is an essential trace element that plays a crucial role in maintaining the health of humans, animals, and certain plants. It is extensively present throughout the Earth's crust and is absorbed by crops in the form of selenates and selenite, eventually entering the food chain. Se biofortification refers to an agricultural procedure that harnesses the mechanisms of crop uptake and the accumulation of exogenous Se through agronomic and genetic strategies to produce Se-enriched crops, ultimately promoting human health. Agronomic strategies for Se biofortification focus on increasing the crop's availability of exogenous Se, while genetic strategies aim to enhance a crop's ability to uptake, transport, and accumulate selenium. Early research primarily concentrated on optimizing Se biofortification methods, improving Se fertilizer efficiency, and enhancing selenium content in crops. However, there has been a growing realization of the substantial impact of selenium in enhancing plant quality, serving as a new driving force for the development of Se biofortification. Therefore, in this work, we provide a comprehensive summary of Se biofortification conducted over the past decade, mainly focusing on Se accumulation in crops and its impact on quality. We discuss various Se biofortification strategies, with an emphasis on the impact of Se fertilizer strategies on crop Se accumulation and their underlying mechanisms. Furthermore, we highlight Se's role in enhancing crop quality and offer perspective on Se biofortification in crop

improvement, providing guidance for future mechanistic explorations and applications of Se biofortification.

Keywords: selenium; biofortification; crops; antioxidants; minerals

1. Introduction

Selenium (Se) is an essential trace element for maintaining human health [1, 2] that can form selenocysteine (SeCys) and serves as the active centre for various selenoproteins. These selenoproteins participate in several vital metabolic processes in the human body, such as antioxidant defence, thyroid hormone production, and cardiac metabolism[3]. Inadequate selenium intake can impair various functions related to human health, leading to a weakened immune system, thyroid dysfunction, and decreased male fertility[4, 5]. Optimal Se intake benefits human health by slowing the ageing process, reducing inflammation, and preventing oxidative stress[6, 7]. Se intake levels in humans rely on the concentration and form of Se in the diet [2]. It has been reported that the assimilation of organic Se from food is approximately 85-95%, while the assimilation efficiency of inorganic Se is approximately 40-50%[8]. Organic Se is more readily absorbed nonspecifically by the human body and plays a more significant role in promoting human health [4, 9]. Therefore, consuming Se-rich foods, particularly those rich in organic Se, can effectively overcome Se deficiency.

Se-rich crops serve as the primary organic Se source for both humans and animals, and their significance for human health cannot be overstated [10, 11]. The levels of Se absorption and accumulation in crops are closely linked to the genetic regulation of Se transport and metabolic mechanisms within crop plants. Previous publications have discussed the process of Se uptake by crop roots and the subsequent transport and metabolism of Se within the plant [12, 13]. In essence, crops initially absorb Se in the form of selenate, selenite, or organic Se compounds such as selenocysteine (SeCys) and selenomethionine (SeMet). Selenates are transported into crops by sulfate transporters, including SULTR1;2 and SULTR1, with SULTR1;2 being the main transporter involved in selenate uptake [14, 15]. Early research indicated that crops absorb selenite through passive diffusion[16]. However, subsequent research has shown the participation of the silicon transporter OsNIP2;1 (Lsi1) aquaporin protein[17] and the phosphate transporter OsPT2 in the uptake of selenite by crops [18]. Upon entering the crop, selenate is initially reduced to selenite. This reduction process involves ATP sulfurylase (ATPS) and ATP reductase (APR)[19]. Subsequently, selenite is further reduced to selenides by selenite reductases or reduced glutathione, forming selenide [20]. Selenide is converted to SeCys through the action of cysteine synthase. However, for crops, the improper incorporation of SeCys into proteins can be detrimental, which is a primary reason why most crops do not accumulate significant amounts of Se. As a result, certain crops can synthesize the volatile compound dimethylselenide (DMSe) from SeMet and excrete it to reduce the biological toxicity caused by excessive Se accumulation. Se hyperaccumulation can convert toxic SeCys into selenocysteine (SeCyst), SeMet, or methylselenocysteine (MeSeCys) to avoid toxicity, thereby accumulating Se concentrations higher than those found in typical plants [21]. These traits make crops the principal source of Se intake for humans and are considered the most ideal candidates for Se biofortification.

Se biofortification is a strategy that strives to enhance bioavailable Se content in edible crops using various methods, including agronomic and genetic strategies [22]. Agronomic strategies for Se biofortification involve adjusting the concentration of Se fertilizers, changing the type of Se fertilizers, modifying the timing of Se application, and implementing agronomic management practices. As a representative Se-deficient region, Finland began adding selenate to all agricultural fertilizers in the 1980s. This approach effectively increased the Se content of crops and alleviated Se deficiency in the local

population [23]. However, the results of Se biofortification in Finland also show that crop uptake of Se from soil-applied Se fertilizers is typically less than 10%[10]. Therefore, to enhance the efficiency of Se fertilization, various agronomic management practices are commonly employed in agricultural practices, including crop rotation, intercropping, irrigation, and microbial inoculation. Genetic strategies for Se biofortification involve the improvement of target crops, either through conventional breeding or transgenic techniques, to enhance their Se uptake and accumulation capabilities. This approach is considered a sustainable, long-term method[24]. Traditional breeding methods combine Se-rich varieties using genetic methods such as hybridization to enhance the Se-rich capacity of the target variety. In contrast, genetic engineering technology has the potential to efficiently introduce genes from naturally Se-rich crops into staple crops, breaking through the limitations of the single-species genetic pool. However, transgenic technology still raises significant ethical concerns in some countries, which makes its widespread adoption and application challenging[25].

As research on Se biofortification advances, an increasing number of studies have suggested that Se, under optimal concentration conditions, promotes crop growth and antioxidant activity. It also increases the content of various macronutrients and beneficial mineral elements in crops while effectively reducing the content of heavy metal elements [26-28]. This may be attributed to Se's activation of crop oxidative stress defence mechanisms, such as the restoration of membrane enzymes [29]. The antagonistic effect of Se on various heavy metal elements in crops is likely because Se reduces the bioavailability of heavy metal elements in the environment and inhibits the crop's ability to absorb and transport heavy metal elements. However, this promoting effect of Se biofortification is not universal and depends on the crop species, genotype and Se fertilization strategy.

In the recent period, there has been a notable surge in research on Se biofortification in crops, and many excellent summaries of this work have been produced [7, 30, 31]. However, due to the substantial diversity in research subjects studied and the Se biofortification methods employed in these studies, the parameters assessed in relation to Se biofortification vary widely. Therefore, there is an urgent need for efforts to collate and establish consistent parameters as evaluation indicators for Se biofortification in crops, providing a reference for future research. The focus of this review is to examine the impact of different Se biofortification strategies on crop Se accumulation and crop quality. We first provide a detailed summary of specific Se biofortification methods, particularly Se fertilization strategies, and their corresponding effects on Se and other indicators related to human health. We also analysed the effects of Se biofortification on crop Se accumulation and quality improvement, addressing possible underlying mechanisms. This review aims to provide guidance for future research and agricultural practices in the field of Se biofortification.

2. Agronomic strategies for Se biofortification

Se biofortification agronomic strategies typically revolve around the addition of Se fertilizers. Previous research has shown that adjustments in Se fertilizer strategies can significantly impact the results of Se biofortification, including the type and dosage of Se fertilizers, as well as the location and timing of Se application. Agronomic management serves as an extension of Se fertilization strategies and encompasses practices such as crop rotation and intercropping, soil and water management, and microbial inoculation. These methods provide support for the widespread application and sustainable development of Se fertilization strategies (Figure.1.). As one of the most easily manageable approaches, agronomic strategies play an indispensable role in the practice of Se biofortification. Therefore, we summarize the effects of different agronomic strategies on crop Se accumulation with the aim of providing guidance for future research and applications of Se biofortification.

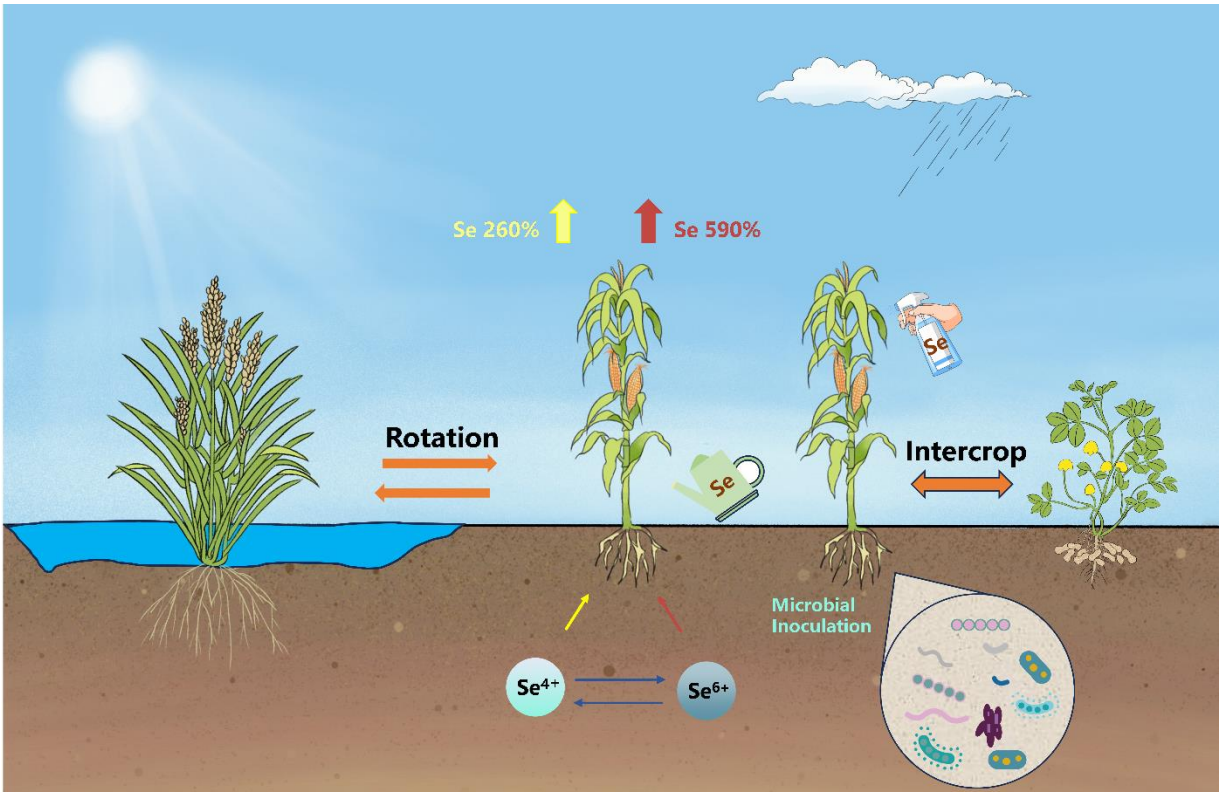


Figure 1. Agronomic strategies for selenium biofortification. Note: The three crops from left to right are rice, corn, and peanuts; the data on crop absorption efficiency for selenate and selenite are derived from the meta-analysis by Ros *et al* [32].

2.1 Se fertilization strategies

2.1.1 Effects of Se species and dosages on crop Se accumulation

Selenate and selenite remain the most commonly used Se fertilizers, although some studies have also utilized organic Se and nano-Se. For most crops, selenate is more readily absorbed than selenite [33-35]. According to the multilevel prediction model by Ros *et al*., the addition of an appropriate dosage of selenate (14 g/ha) and selenite to crop roots resulted in a significant increase in total Se content in the crops, with changes of +590% and +260%, respectively (Figure.1.) [32]. The higher absorption efficiency of selenate by crops might be due to its reduced tendency to adsorb to the soil and its easier transport from the roots to the stems and leaves [36, 37]. Previous research has suggested that crops supplied with selenite primarily accumulate organic Se, while those supplied with selenate mainly accumulate selenate[38]. The conversion of selenate to selenite appears to be the step that limits the rate of selenate assimilation into organic Se [39]. D'Amato *et al*. treated rice seeds with 135 mg L^{-1} selenite and selenate. The results revealed that in the shoots treated with selenite, the organic Se content was 23.8 μg g^{-1} DM, accounting for 93.8% of the total Se content. In comparison, in rice seedlings treated with selenate, the organic Se content was 24.9 μg g^{-1} DM, representing 32.5% of the total Se content [40]. This suggests that although the conversion of selenate to organic Se in crops is relatively low, the higher absorption of selenate by crops results in greater accumulation of both organic and inorganic Se. In general, inorganic Se is considered toxic to humans, while organic Se is beneficial [41]. In summary, selenate seems to function as a more effective Se fertilizer, but attention should be directed towards possible health hazards associated with the excessive accumulation of inorganic Se in crops. Selenate is a more efficient selenium species, but it raises concerns about the potential health risks. The application of selenite may provide a safer approach for organic Se food production. However, due to

selenite's higher soil adsorption[37] and lower crop uptake and translocation rates, its biofortification efficiency might be insufficient.

In general, the level of Se accumulation in crops is positively correlated with the concentration of Se fertilizer [42-44]. However, it is incorrect to judge the optimal Se fertilizer dosage solely based on the total Se accumulation in crops. The utilization efficiency of Se fertilizer and the most suitable Se form and concentration for human consumption must also be considered. For instance, in Hu *et al*.'s study on Se biofortification of *H. ericium erinaceus*, it was observed that under selenate treatment conditions ranging from 0.5 to 80.0 μg/g, the bioconcentration factor of Se in the mushroom fruiting bodies exceeded 1. However, under the treatment condition with 100 μg/g selenate, the bioconcentration factor dropped below 1[34]. Another study demonstrated that when the Se fertilizer dosage increased from 50 g Se/ha to 100 g Se/ha, the proportion of organic Se in peanuts decreased from 88.2% to 80.1%[45]. These studies indicate that while increasing Se fertilizer concentration can boost Se accumulation in crops, it may also lead to decreased Se fertilizer and organic Se conversion efficiency, potentially causing excessive Se retention and posing a threat to environmental health. Furthermore, considering the narrow concentration range of Se beneficial for human consumption, it is advisable to select appropriate Se fertilizer concentrations for different crops.

2.1.2 Effect of crop fertilization site and time on Se accumulation

Based on the mechanisms of Se uptake in crops, foliage and roots are the two most common application sites for Se supplementation. Root application of Se can substantially boost Se concentration in crops [46]. Liu *et al*. revealed that within a Se concentration range that did not affect the biomass and yield of wheat, root application of Se could increase the Se content in wheat kernels by more than 17 times. [43]. These studies demonstrate that root application of Se is highly effective for improving crop Se accumulation, making it a practical and viable approach. However, the utilization rates for root-applied Se in crops is generally low, and long-term root application may lead to increased soil toxicity [30]. Comparatively, foliar Se treatment can utilize Se fertilizers more effectively [32]. Se can enter the crop through the leaf, reducing the environmental impact during this process and shortening the distance for Se transport to crop seeds[47]. Xia *et al*. reported that foliar-applied Se in purple-grain wheat led to higher Se accumulation in grains, stems, leaves, awns, and spike tips compared to root application [44]. Currently, foliar Se application has become a commonly used approach for Se biofortification in staple crops such as wheat and rice [35, 48-52].

The transport of Se within crops is closely related to the growth stage of the crop. It is difficult for rice to oxidize and transport absorbed selenite to the aboveground parts during the early growth stage, but it can effectively transport and accumulate Se in the grains during the tillering or heading stage[53]. Therefore, strategically timing Se application in crops can enhance their Se content in the edible portions. Wang *et al.* suggested that foliar Se application to wheat during the grain-filling stage, as opposed to earlier growth stages or other stages, results in the highest grain Se content[35]. Wheat leaves treated with Se during the grain-filling stage have significantly lower Se content than those treated during the vegetative growth stage [54]. These studies indicate that during the grain-filling stage, crops tend to translocate Se from leaves to seeds, making Se application at this stage effective for achieving high Se content in crop seeds.

Overall, Se fertilization is a straightforward and effective method for Se biofortification. However, poorly planned Se application methods do not align with the principles of "precision agriculture" and can lead to some degree of Se resource waste and soil pollution issues. Therefore, we have summarized the impacts of different Se fertilization strategies on crop Se accumulation, aiming to provide guidance for future research and Se application schemes in agricultural production.

2.2 Agronomic management strategies

2.2.1 Crop rotation and intercropping

Crop rotation systems can enhance agricultural ecosystem functions, including improving soil fertility, maintaining soil structure, and increasing soil microbial diversity [55]. As a traditional agricultural practice, crop rotation has been demonstrated for decades to increase the bioavailability of micronutrients such as Fe, Cu, Zn, and Mn [56, 57]. Recently, there has been a growing interest in Se biofortification, and several studies have observed the significant role of crop rotation in Se biofortification. For example, in a barley-red clover-potato rotation system, applying Se through foliar spray to barley alone increased Se levels in barley grains and stems, red clover leaves, and potato tubers [58]. In the foliar application of Se within the crop rotation system involving winter wheat and summer maize, maize almost completely consumes the residual Se in the soil [59]. These findings illustrate that the differences in Se uptake and accumulation capabilities among different crops in rotation systems, compared to monoculture systems, result in the efficient utilization of residual Se in the soil. Additionally, the increase in crop species diversity and microbial diversity in rotation systems may contribute to the higher levels of bioavailable Se in the soil [30].

Although intercropping is an ancient agricultural practice, it can still effectively address some of the major challenges in modern agriculture, including soil degradation, crop yield increase, and environmental degradation[60]. According to the stress gradient hypothesis [61], as environmental stress increases, crops are more likely to exhibit net positive (facilitative) interactions with other crops [62]. Therefore, the introduction of Se as a nonessential element for crops might lead to facilitative interactions between crops in intercropping systems. Recently, Tang *et al.* studied the impact of intercropping on Se levels in bok choy, lettuce, and radishes. The findings revealed that, compared to monoculture, intercropping elevated Se content in the edible parts of bok choy and radishes [63]. Similarly, Lin *et al*. reported that intercropping cherry tomatoes with three wild eggplant species of the Solanum genus (diploid, tetraploid, and hexaploid) resulted in a 13.73%, 17.49%, and 26.50% increase in Se content in cherry tomato seedlings compared to cherry tomato monoculture [64].

2.2.2 Soil and water management

The soil pore structure is a crucial factor that affects root growth and function, the transport of solution ions to the crop root surface, and processes such as solute leaching in the rhizosphere[65]. Agricultural practices typically manipulate soil pore structure through soil compaction or tillage. The anaerobic conditions in compacted soil may lead to soil microorganisms reducing bioavailable selenates and selenite into elemental Se that cannot be absorbed by crops[66]. Zhao *et al*. suggested that restricted root growth in compacted soil might lead to a significant decrease in Se concentration in wheat grains [67]. However, there are also studies that have arrived at different conclusions. For instance, some reports suggest that appropriate soil compaction can reduce soil porosity, increase the root-soil solution interface, and enhance the uptake of trace elements by crops[68, 69]. Similarly, tillage, the most traditional soil management practice, remains a subject of debate in organic agriculture[70], including its impact on Se biofortification. Lessa *et al*. found that tillage reduced soil Se adsorption, bringing Se from deep soil layers to the surface, thereby increasing crop-available Se content [71]. Ozpinar *et al*. reported varying degrees of increased Se concentrations in all corn tissues under three tillage systems (ploughing, rotary tillage, and chisel ploughing)[72]. However, the work of Lopez-Bellido *et al*. suggested that no-tillage systems did not create stronger soil reducing conditions than traditional tillage systems, and tillage practices did not seem to affect Se uptake and accumulation in wheat[73]. Therefore, it is evident that soil compaction/tillage can influence the Se biofortification of crops by increasing/reducing bioavailable Se content or promoting/inhibiting crop growth[30]. More research is required to clarify the geochemical behaviour of Se in agronomic practices and understand the de-

tailed processes through which agronomic management practices influence Se biofortification.

As water scarcity becomes an increasingly pressing issue, water management has become a focal point in agricultural research. Irrigation is one of the most common and impactful water management measures in agricultural systems [74]. Irrigation provides a temporary Se reservoir for crops, significantly influencing their Se concentration and forms [75]. Zhao *et al*. found that irrigation during the wheat growth period doubled its grain yield[67], while the Se concentration decreased by 10 times, which may be due to increased yield and leaching of soil-available Se caused by irrigation[76]. Recent research supports this notion. Ma *et al*. conducted an eight-year monitoring and investigation of high-Se and adjacent soils, revealing that irrigation water led to Se leaching and migration in the soil[77]. Moreover, irrigation can alter soil redox conditions and pH. Wang *et al*. discovered that aerobic irrigation, to some extent, increased soil pH, oxidation–reduction potential, bioavailable Se content, and enhanced Se concentration in grains[78]. In summary, the impact of irrigation on Se biofortification is complex. Aerobic irrigation results in the transformation of Se into forms with higher bioavailability, but Se dissolution and migration during irrigation reduce the soil Se content.

2.2.3 Microbial-assisted biofortification

The low bioavailability of Se fertilizers in agronomic biofortification strategies has sparked significant interest in microbial-assisted Se biofortification. Rhizosphere bacteria and arbuscular mycorrhizal fungi (AMF) are the two most commonly employed microorganisms for Se biofortification, as they can effectively enhance crop Se uptake [79, 80].

AMF are commonly associated with crop roots. They not only provide Se to crops through an extensive mycelial network [81] but also alter the chemical compounds and pH of crop roots in the rhizosphere through metabolic activities such as the secretion of extracellular phosphatase, thereby enhancing Se bioavailability in root soil [82, 83]. Chen *et al.* found that the inoculation of AMF notably enhanced various forms of selenium present in the rhizosphere soil, thereby effectively enhancing the content of organic Se in rice [84]. Additionally, the enhanced Se uptake in crops through AMF is associated with their capacity to encode sulfate transport proteins. AMF induce the production of specific sulfate transport proteins in crops, leading to increased Se uptake [85].

Bacteria play a pivotal role in the Se biogeochemical cycle [86], especially within the rhizosphere of plants. Bacteria capable of accumulating selenium from the soil and supplying it to crops are referred to as selenium bacteria[87, 88]. Se bacteria utilize metabolic processes to chemically transform Se (oxidation, reduction, or methylation) and assimilate it within their cells through respiration[89]. Generally, based on the location of bacterial inoculation, Se bacteria can be classified into rhizosphere bacteria and endophytes. Yasin reported that the application of YAM2 (a rhizobacterial strain with 99% similarity to *Pichinotyi* Bacillus) in wheat kernels and stems increased Se levels by 167% and 252%, respectively [90]. The study by Feng *et al*. demonstrated that a bacterial consortium synthesizing iron carriers led to a 68.7% increase in soil-bioavailable Se and a 92.2% improvement in crop Se uptake efficiency[91]. These findings indicate that Se bacteria not only promote the production of bioavailable Se in the rhizosphere but also enhance crop Se uptake capabilities simultaneously. In comparison, endophytic bacteria have a weaker regulatory effect on Se in crop rhizosphere soil, which might not be conducive to Se accumulation in crops. However, endophytic bacteria have stronger associations with crops, are protected by crop tissues and have more stable growth environments. Consequently, they often provide greater benefits to crops in terms of promoting growth, nutrient accumulation, disease suppression, and environmental stress resistance[92, 93]. For instance, Trivedi reported that soybean crops treated with endophytic Se bacteria MGT9 showed improved growth under drought conditions, and the Se biofortification effect in soybean crops increased by 7.4 times. [87].

These studies indicate that microbial inoculation of crops can enhance crop Se transport capacity and the Se forms in the crop rhizosphere. This effectively compensates for the limitations of Se fertilization strategies and represents a promising auxiliary technology for Se biofortification.

3. Genetic strategies for Se biofortification

The utilization efficiency of Se fertilizers in agronomic practices is influenced by various factors, with genetic constraints in crops being a key factor. Se genetic biofortification researchers aim to harness gene strategies to cultivate specific crop species or genotypes capable of accumulating adequate Se in their edible parts by thoroughly understanding the mechanisms of Se absorption and metabolism by crops[12]. Generally, gene-based Se biofortification strategies involve improving the genes of target crops through traditional breeding and genetic engineering techniques to achieve enhanced Se uptake and accumulation in the target crop[94]. Traditional breeding methods have lower research interest but have a higher success rate, making them a reliable biofortification approach [94]. However, breeding technology is characterized by a lengthy varietal development period and also faces challenges in surpassing limitations associated with genetic resources. Transgenic technology has the potential to overcome genetic limitations by introducing genes from other species, but its high cost and ethical concerns make it challenging to widely implement at the moment.

3.1 Breeding techniques for gene improvement in crops

Traditional breeding methods involve genetic approaches, such as hybridization, to combine varieties rich in the target nutrient to improve the genetics of crops [95] (Figure.2 a and b). There is wide genetic variability in Se concentrations in potato tubers[96], soybean seeds[97], rice[98, 99], wheat grains, and various leafy vegetables [100]. For example, Zhao *et al*.[101] isolated a rice mutant, cadt1, from an ethyl methanesulfonate (EMS)-mutagenized population of indica rice varieties. The mutation in the OsCADT1 gene led to a 2.4 times increase in the maximum rate of selenate absorption in cadt1, indicating a significant enhancement in selenate uptake in the mutant. Generally, traits related to Se uptake in crops are quantitative traits, and these traits are under genetic control [102]. Quantitative trait loci (QTL) mapping can breakdown complex quantitative traits into several genetic loci, helping to identify Se concentration QTL. Studying the genetic characteristics of different crops and identifying QTL related to Se uptake and accumulation is crucial for crop breeding and Se biofortification. Se concentration QTL have been identified in various common crops, including rice[103, 104], wheat[105], and lentils[106]. A recent study on QTL related to selenate tolerance in a recombinant inbred line (RIL) population derived from a cross between *Arabidopsis thaliana* genotypes Ler-0 and Col-4 revealed that genetic loci on chromosomes 1, 3, and 5 are associated with selenate tolerance[107]. This discovery aligns with the outcomes observed in the hybrid experiments conducted on *Arabidopsis thaliana*. In recent times, genome-wide association studies (GWAS) have been employed to pinpoint the Se concentration QTL in crops, notably in rice[108], wheat[109], and legumes[110]. GWAS is based on detecting associations between genotypes and correlated traits based on linkage disequilibrium in a sample population [111]. For example, Zhang *et al*. detected three QTL for Se concentration in rice grains from the entire genome of 698 accessions, which constituted two subsets (indica/Xian, X-set, and japonica/Geng, G-set) [112]. The application of QTL mapping and GWAS allows for the rapid identification of genetic loci related to Se concentration traits, significantly enhancing the efficiency of traditional breeding techniques and advancing the research and application of traditional breeding techniques in Se biofortification.

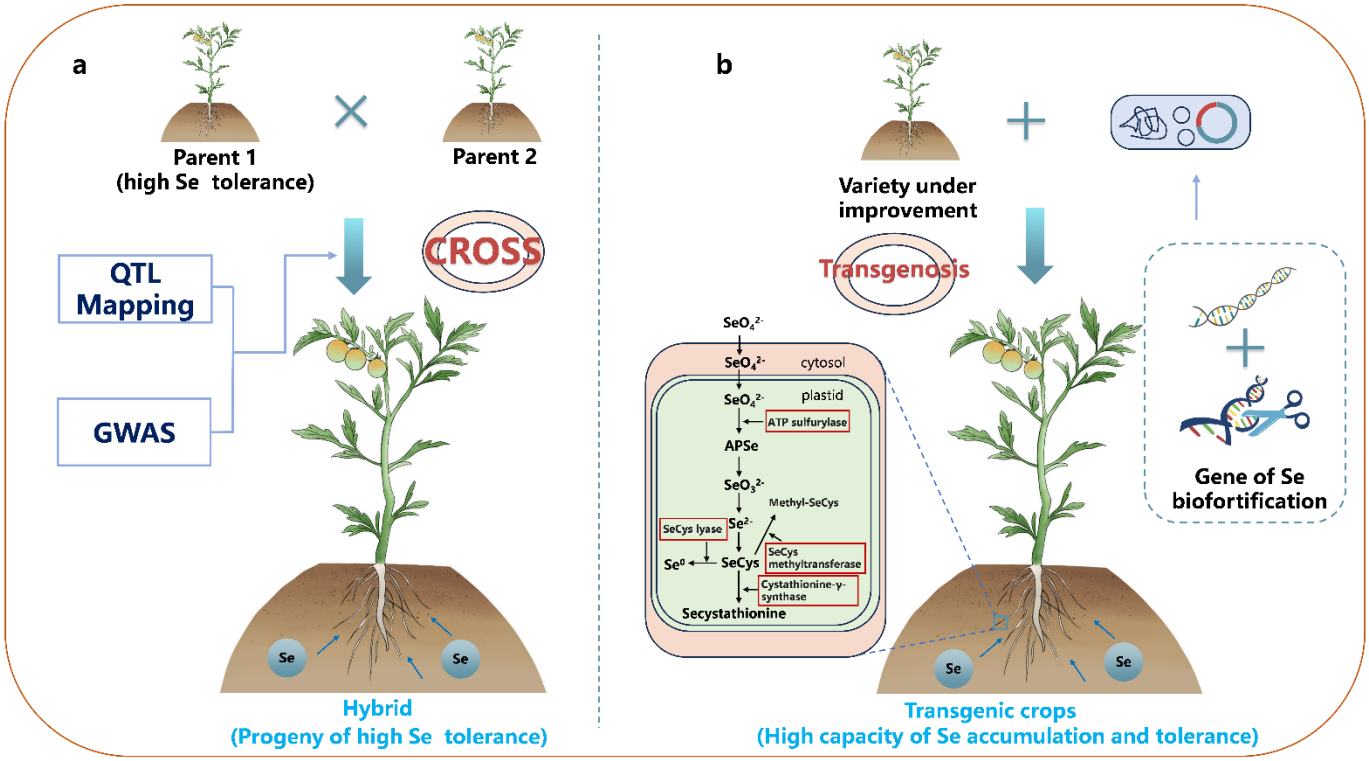


Figure 2. Genetic strategies for Se biofortification. (a) Breeding techniques; (b) Transgenic technology; Enzymes outlined with a red border are those overexpressed using transgenic technology. Note: QTL Mapping: quantitative trait loci mapping; GWAS: genome-wide association studies.

3.2. Transgenic technology expanding the traditional crop gene pool.

Traditional breeding techniques depend on the genetic diversity of crop varieties, and incorporating desirable traits into target varieties takes many generations[113]. In cases of limited or absent genetic variation in Se uptake across diverse crop varieties , transgenic technology can be used to introduce genes from other species into crops to obtain varieties capable of Se enrichment[114].

Transgenic technology can boost selenium absorption in crops by overexpressing genes associated with Se uptake and enhancing the crop's resilience, storage, and volatility of selenium. This process involves augmenting the conversion of selenate into SeCys and the alterations of SeCys into volatile dimethylselenide, SeCys methylation, and the conversion of SeCys into elemental Se (Figure.2. c)[115]. Li *et al*. [116] simultaneously overexpressed genes encoding human selenocysteine lyase (HsSL) and selenocysteine methyltransferase from *Astragalus bisulcatus* in rice. After the addition of selenate and selenite, the newly obtained transgenic rice exhibited an increase in fresh weight, with Se accumulation levels approximately 38.5% and 128.6% higher than those of the wild-type rice. Furthermore, it is noteworthy that Se hyperaccumulators, while not well suited for direct biofortification, serve as ideal species for providing genes for Se biofortification. Brummell *et al*. increased the efficiency of MeSeCys production in tomatoes by introducing the SMT1 gene from the Se hyperaccumulator *A. bisulcatus*. The newly cultivated tomato variety stored as much as 16% of its overall Se content in the form of MeSeCys[117]. It can be concluded that transgenic technology provides a more efficient strategy for improving Se biofortification in crops compared to traditional breeding methods. However, further research may be needed to address concerns and potential challenges associated with the use of this technology.

4. Impact of Se biofortification on crop quality

Se biofortification is a promising agricultural practice that not only increases the Se content in crops but also enhances their overall nutritional quality, providing a range of essential nutrients and bioactive compounds that benefit human health[118]. The primary beneficial nutrients influenced by Se biofortification in crops include macronutrients (such as proteins, carbohydrates, lipids, and vitamins), antioxidant compounds (phytochemicals, carotenoids, flavonoids, vitamin C, etc.), and mineral elements (calcium, magnesium, potassium, manganese, zinc, iron, copper, etc.)[26-28]. Additionally, as a practical agricultural application technique, Se biofortification should consider crop growth parameters and the presence of toxic heavy metal elements as crucial evaluation criteria.

4.1. Influence of Se biofortification on crop growth

Crop growth status is a crucial economic indicator in agricultural practices. Typically, the antioxidant activity of crops, as well as parameters such as root, stem, or leaf length or biomass and grain yield, can reflect the growth status of crops. This section focuses on elucidating the impact of Se on crop antioxidant activity, a vital indicator of crop growth, particularly in the context of growth under stressful conditions.

The impact of Se on crop development is significantly linked to Se fertilization strategies and the specific crop species or genotypes (Table 1). Field experiments with black-grained wheat have shown significantly higher yields in Se-rich regions than in Se-poor areas [43]. Saidi observed that when sunflower seedlings were exposed to 20 μM Cd treatment, root and leaf fresh weights decreased by approximately 69% and 57.5%, respectively [119]. However, adding 5 μM Se increased the fresh mass of leaves and roots by approximately 48% and 59.50%, respectively. This could be due to Se activating the crop's antioxidant defence mechanisms. Se-induced enhancement of antioxidant activity alleviates the inhibitory effects of heavy metals on crop growth, including the restoration of reduced photosynthesis caused by heavy metals, increased levels of various bioactive compounds in crops, and elevated antioxidant enzyme activity[29, 120, 121]. For example, research by Newman demonstrated that the oxygen radical absorbance capacity (ORAC) values of chives, basil, and cilantro increased by 152.2%, 68.6%, and 66.0%, respectively, under optimal sodium selenate conditions[122]. However, importantly, excessively high Se concentrations can harm crop growth, as many studies have shown [40, 122-124]. Studies on potatoes conducted by de Oliveira showed that a Se dosage of 0.75 mg/kg increased potato tuber yield by 4%, but when the Se dosage increased to 5 mg/kg, the tuber yield decreased by 17%[125]. Similar conclusions have been drawn for wheat[43], rice[40], and mushrooms[126]. This may be because high Se doses have a pro-oxidative effect on crops, leading to increased concentrations of reactive oxygen species (ROS) and H_2O_2, as well as lipid peroxidation. Insufficient levels of reducing substances in crops, such as glutathione (GSH), thiols, ferredoxin, and reduced coenzyme II (NADPH), cannot simultaneously meet the demands of both Se assimilation and ROS quenching[29], causing a decline in the crop's antioxidant capacity and impaired growth[127-129]. For instance, it has been reported that the H_2O_2 content in coffee leaves treated with Se fertilization at doses of 10-40 mg/L was inversely correlated with the Se fertilizer concentration. However, as Se concentrations increased further (80-160 mg/L), the H_2O_2 content gradually rose[130].

Apart from the Se dosage, the influence of Se biofortification on crop development, including antioxidant activity, is closely related to the type of Se fertilizer used. In most cases, the trends in the impact of various Se forms on antioxidant activity (either positive or negative effects) are consistent, but the degree of impact varies (Table 1). It is suggested that selenite may have a more significant toxic effect on crops than selenate because selenite is more readily assimilated into organic Se compounds such as SeCys and SeMet, potentially disrupting typical production of proteins [131]. For instance, Groth reported that, compared to selenate, the application of selenite resulted in lower antioxidant activity in the 'Golden Delicious' apple genotype [27]. However, there are also

studies reporting different conclusions. D'Amato *et al*., for example, reported that under high Se concentrations, selenate application exhibited a stronger suppression of rice seedling growth, leading to delayed germination and development of rice seedlings [40].

In summary, Se biofortification generally promotes crop growth, but this stimulatory effect has a threshold, and excessive Se accumulation can impair crop growth. Ideally, Se biofortification applications should ensure that crops accumulate Se levels beneficial to human health while maximizing crop growth.

Table 1. The Effects of Selenium Application on Growth Parameters (Including Antioxidant Activity) and Macronutrient Content in Different Plants.

Species	Applications	Growth Parameters	Saccharides	Proteins	Fats	Antioxidant activity	Antioxidant enzyme	References
Triticum aestivum, L. cv.Baegjoongmil microgreens	Sodium selenite 0.125- 1.0 mg Se/L-hydroponic	Yield ↓* Microgreen weight ↓ Microgreen height ↓	–	–	–	NSA ↑0.25 mg/L ABTS NS; DPPH NS	SOD ↑0.125,1.00 mg/L	[132]
Oryza sativa L.'Ariete' grains	Sodium selenate 30-300 g Se/ha – foliar	–	Total Sugars ↑60-300 Se/ha	↑120-300 g Se/ha	↑180g Se/ha	–	–	[123]
Ipomoea aquatica Forsk. 'XGDB'	Selenite 0.2 mg/L Se – Foliar	Biomass NS	–	NS	–	MDA NS	SOD NS; POD NS; CAT NS;	[26]
Triticum aestivum L. Shoots 'BRS 264'	Sodium selenate 12-120 g/ha Se – foliar	Yield ↑	Total Soluble Sugars ↑ Sucrose ↑21,120 g/ha Se	NS	–	MDA NS H_2O_2 NS	APX ↑12-38 g/ha; CAT NS; SOD NS	[54]
Solanum tuberosum L. Tubers	Sodium selenite 0.75-5.0 mg/kg Se	Production ↑0.75 mg/kg ↓3-5 mg/kg	–	–	–	MDA ↑ 3.0-5.0 mg/kg H2O2 ↓	CAT ↑ 1.5-3.0 mg/kg SOD ↑1.5-5.0 mg/kg	[125]
Coffea arabica red Itucaí Leaves	Sodium selenate 10-160 mg/L – foliar	Yield ↑10-40,120 mg/L	–	–	–	MDA ↓; H_2O_2 ↓20-80 mg/L, ↑160mg/L	CAT ↑20,120-160 mg/L APX ↑20-160 mg/L SOD ↑20-160 mg/L	[130]

Effects in comparison to control groups without selenium application; Note: * (↑) - increase; (↓) - decrease; NS - not significant.

4.2. Effect of Se biofortification on small-molecule antioxidant contents in crops

In response to abiotic stressors such as Se, crops increase the synthesis of certain small-molecule antioxidants to cope with environmental changes [133]. These small-molecule antioxidants are vital in the growth processes of crops as well as in regulating the generation of ROS in the human body when consumed through the diet or as supplements. This, in turn, effectively protects cells and tissues from chronic oxidative

damage [134]. Huang *et al*. reported that germinating black soybeans (GBS) exposed to a Se concentration of 25 mg/L exhibited the highest total phenolic content, with GBS treated at 50 mg/L showing a 50.3% increase in total phenolic acid levels[135]. A significant correlation between Se fertilizer application and crop vitamin C content has been observed in various crops, including wheat[132], water spinach [26], Indian mustard (*Brassica juncea* L.)[136], and spinach[137], among others (Table 2). Crop pigments have gained increasing attention due to their environmentally friendly and nontoxic characteristics, along with beneficial functions such as antimicrobial and antioxidant properties and enzyme induction[138]. Numerous reports have suggested that the addition of an appropriate Se supplementation can enhance the chlorophyll accumulation in crops and help mitigate chloroplast damage caused by environmental stressors [130, 132, 139].

Se, at its optimal concentration, facilitates the synthesis of small-molecule antioxidants in crops, demonstrating its beneficial role in promoting human antioxidative defences. However, importantly, Se's promotion of these antioxidants exhibits a threshold effect. Therefore, Se fertilization strategies need to be adjusted to maximize the utilization of Se and antioxidants within crops while avoiding potential damage caused by excessive Se.

Table 2. The Impact of Se Application on Bioactive Compounds and Crop Pigments in Various Crops.

Crop	Applications	Bioactive compounds	Crop pigments	References
Oryza sativa L.	**Sodium selenite**	**Soluble Free Phenolic Acids (PA) ↑* 45-405 mg/L**	**Total chlorophyll content (TChlC)↑15-45 mg/L, ↓135-405 mg/L**	[40]
(Shoots of 10-Day Old Rice Sprouts)	15-405 mg Se/L – plastic trays	Bound PA ↑45 mg/L, ↓15, 135-405 mg/L Soluble Conjugated PA ↑	Total Carotenoid content (TCC) ↓45-405 mg/L	
Oryza sativa L.	Sodium selenate	Soluble Free PA ↑	TChlC ↓45-135 mg/L	
(Shoots of 10-Day Old Rice Sprouts)	15-135 mg Se/L – plastic trays	Bound PA ↓	TCC ↓45-135 mg/L	
Fragaria × *ananassa* cv. Fruits	Sodium selenate	Total phenolic content (TPC) NS; Total Flavonoids ↓	–	[42]
	10,100 μM Se – hydroponic	Total Flavonols ↓		
Brassica juncea L. Leaves	Sodium selenate	Vitamin C ↑; Carotene NS	Chlorophyll a NS; Chlorophyll b ↑	[136]
Coriandrum sativum L.	50 mg Se/L Sodium selenate	Flavonoids ↑ Total polyphenols ↑16 μM	β-carotene ↑8 μM, ↓16 μM	[140]
	8 ,16 μM Se – capillary mat		Lutein ↓	
Ocimum basilicum L. 'green basil'	Sodium selenate	Total polyphenols ↑8 μM	β-carotene ↓	
	8 ,16 μM Se – capillary mat		Lutein ↑8 μM, ↓ 16 μM	
Spinacia oleracea L.	Sodium selenate	Vitamin C NS	Chlorophyll a ↓; Chlorophyll b ↓	[137]
male crop Leaves	0.28 mM Se – foliar		TChlC ↓; Carotenes ↓	
Spinacia oleracea L.	Sodium selenite	Vitamin C ↑	Chlorophyll a ↑; Chlorophyll b ↑	
male crop Leaves	0.28 mM Se –		TChlC ↑; Carotenes ↑	

	foliar		
Spinacia oleracea L. female crop Leaves	Sodium selenate 0.28 mM Se – foliar	Vitamin C ↑	Chlorophyll a NS; Chlorophyll b ↑ TChlC NS; Carotenes ↑
Spinacia oleracea L. female crop Leaves	Sodium selenite 0.28 mM Se – foliar	Vitamin C ↑	Chlorophyll a NS; Chlorophyll b ↑ TChlC ↑; Carotenes ↑

Effects in comparison to control groups without selenium application; Note: *(↑) - increase; (↓) - decrease; NS - not significant.

4.3. Impact of Se biofortification in crops on element accumulation

4.3.1. Impact of Se biofortification on human health-related mineral elements

Se biofortification is a feasible method to increase the Se content in human food, as well as other essential dietary elements such as calcium, potassium, sodium, magnesium, iron, copper, manganese, zinc, and more. The increased content of these beneficial dietary elements in Se-biofortified foods can render them more advantageous than Se supplements. Pannico *et al*. reported on the variation in mineral elements among four different microgreen genotypes under the same Se treatment conditions [140]. The results indicated that the levels of elements such as Fe, Zn, and Mn increased in cilantro and purple basil, while conversely, green basil and lettuce showed a decrease in the accumulation of Fe and Zn. Some studies have shown the influence of Se fertilization strategies on the accumulation of mineral elements in crops. For instance, Golubkina found that applying selenates to male spinach crops resulted in decreased Mg levels, with no significant difference in Ca content, while the opposite was observed when selenite was used. [137]. When sodium selenite was applied to wheat leaves and soil, foliar Se application increased the levels of Ca and Zn in wheat grains, with no significant difference in Fe content, while soil Se application had the opposite effect, leading to no significant differences in Ca and Zn content but a significant reduction in Fe content[44]. Given these findings, some studies have also started to explore the relationships between these factors and the content of various mineral elements. A recent study indicated that foliar spraying of selenates not only resulted in changes in mineral elements in kale crops but also altered the quantitative relationships between elements. For instance, the correlation coefficient between Se and Si significantly increased, while the coefficients between Zn and P and Co notably decreased[141].

Se biofortification can yield either positive or negative impacts on human intake of beneficial mineral elements. Further research is needed to identify which specific mineral elements are adversely affected and to what extent. Additionally, to mitigate potential reductions in human intake of mineral elements, Se biofortification should prioritize nonstaple foods.

4.3.2. Influence of Se biofortification on toxic heavy metals

Heavy metals can cause damage to human or crop cells at extremely low concentrations. The incorporation of heavy metals into proteins may lead to the inhibition of protein activity or structural damage, induce cellular oxidation, or reduce antioxidants, resulting in crop cell damage [142, 143]. Several studies have demonstrated that Se, under appropriate concentration conditions, can effectively reduce the accumulation of toxic heavy metals such as Cd, Hg, As, Pb, and Cr in crops and alleviate toxicity (Table 3). There have been a significant number of detailed studies [29, 144-147] summarizing the mechanisms of Se protection in crops, which are briefly discussed in this paper. First, Se can alter the chemical forms of heavy metals in the soil, thereby reducing their bioavailability and decreasing crop uptake [148]. Zhang found that due to the stronger affinity of Se for binding with Hg compared to S, Se can replace the S atom in methylmercu-

ry-cysteine (MeHg-Cys) to form biologically unavailable methylmercury-selenocysteine (MeHg-Sec) complexes, significantly reducing the biological toxicity of Hg[149]. Second, Se can reduce the toxicity of heavy metals to crops by inhibiting the translocation of heavy metals from the roots to the aboveground parts and reducing their accumulation in the edible parts of crops[150]. Zhang *et al.* demonstrated that with the increase in Se content in rice soil, the transfer of inorganic mercury and methylmercury to the aerial portions of rice continually decreased, and the content of inorganic Se in grains was inversely proportional to inorganic mercury and methylmercury[151]. Further studies showed that Se supplementation resulted in an obvious reduction in Cd content in the shoots, roots, and leaves of tomato seedlings, indicating that Se simultaneously suppressed the processes of Cd entering crops and translocating within crops[152]. Additionally, the change in the content of heavy metals in Se-supplemented crops may primarily depend on the type of crop and the type of heavy metals rather than the type and dosage of Se fertilizer (Table 3). For instance, soil-applied Se led to a decrease in Pb in purple-grain wheat ('202w17')[44] but had no effect on the grain Pb in three other wheat varieties (Xihei 88, Heidali, and Pubing 151)[43]. In experiments on Se biofortification of lion's mane mushrooms, it was found that the application of 40 μg/g of selenite and SeMet both resulted in a decrease in As content in the fruiting bodies but increased the Cr content[34].

Table 3. The Effects of Se Biofortification on the Content of Cd, Pb, Cr, Hg, and As in Different Crops.

Crop	Application	Cd	Pb	Cr	Hg	As	References
***Triticum aestivum* L.**	**Se ore powder**	**–***	**NS**	**NS**	**NS**	**NS**	[43]
'Xihei 88' Grain (black-grained wheat)	1,080-4,320 g Se/ha – soil						
Triticum aestivum L.	Se ore powder	–	NS	NS	NS	NS	
Heidali' Grain (black-grained wheat)	1,080-4,320 g Se/ha – soil						
Triticum aestivum L.	Se ore powder	–	NS	NS	NS	NS	
H.ericium erinaceus fruiting bodies	Selenate	NS 40 μg/g	–	NS 40 μg/g	↑40 μg/g	NS 40 μg/g	[34]
	0.5-200 μg Se/g – substrate						
H.ericium erinaceus fruiting bodies	Selenite	↓40 μg/g	–	↑40 μg/g	NS 40 μg/g	↓40 μg/g	
	0.5-200 μg Se/g – substrate						
H.ericium erinaceus fruiting bodies	SeMet	NS 40 μg/g	–	↑40 μg/g	↓40 μg/g	↓40 μg/g	
	0.5-200 μg Se/g – substrate						
Brassica juncea L. Leaves	Sodium selenate	↓	NS	NS	–	NS	[136]
	50 mg Se/L						
Triticum aestivum L. 202w17 (purple-grain)' Grains	Sodium selenite 10 mg Se/ml – foliar	↓	↓	↓	–	–	[44]
Triticum aestivum L.	Sodium selenite	↓	↓	NS	–	–	
' 202w17 (purple-grain)' Grains	50 mg Se/kg – soil						
Triticum aestivum L.	Sodium selenite	↓	↓	↓	–	–	`

Effects in comparison to control groups without selenium application; Note: * (↑) - increase; (↓) - decrease; NS - not significant.

Assessments concerning the impact of Se biofortification on the accumulation of heavy metals in edible crops have reported a significant decrease in Cd, Hg, As, Pb, and Cr content (Table 3). This suggests that Se biofortification restricts the entry of heavy metals into the food chain through crops in most cases, effectively reducing heavy metal stress in the soil-crop-human system.

5. Conclusions and perspective

Se is an essential element for the formation of various crucial selenoproteins in both humans and animals, including glutathione peroxidase (GPx) and thioredoxin reductase (TXNRD). Se biofortification strategies in crops have been widely applied to alleviate Se deficiency symptoms in regional populations. Over the past decade, significant progress has been made in optimizing Se biofortification methods and diversifying the enriched crop species. The response mechanisms of crops to exogenous Se have also been elucidated to some extent. Furthermore, there has been a growing interest in the role of selenium in improving plant quality, leading to a rapid increase in related research. However, the current abundance of selenium biofortification studies, along with significant variations in target species, growing conditions, and selenium fertilizer strategies, make it challenging to draw comprehensive conclusions from these studies. Therefore, this review aims to promote human health by summarizing and evaluating the agronomic and genetic strategies of selenium biofortification, with a particular emphasis on its impact on crop quality. Considering that selenium biofortification is an agricultural endeavour that addresses a large population, we recommend that future research should focus on the selection of plant species and fortification methods. Priority should be given to exploring fortification strategies for staple crops and understanding the mechanisms of selenium enrichment. Additionally, future research should emphasize the economic benefits of selenium biofortification, cost reduction, and improving plant quality.

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