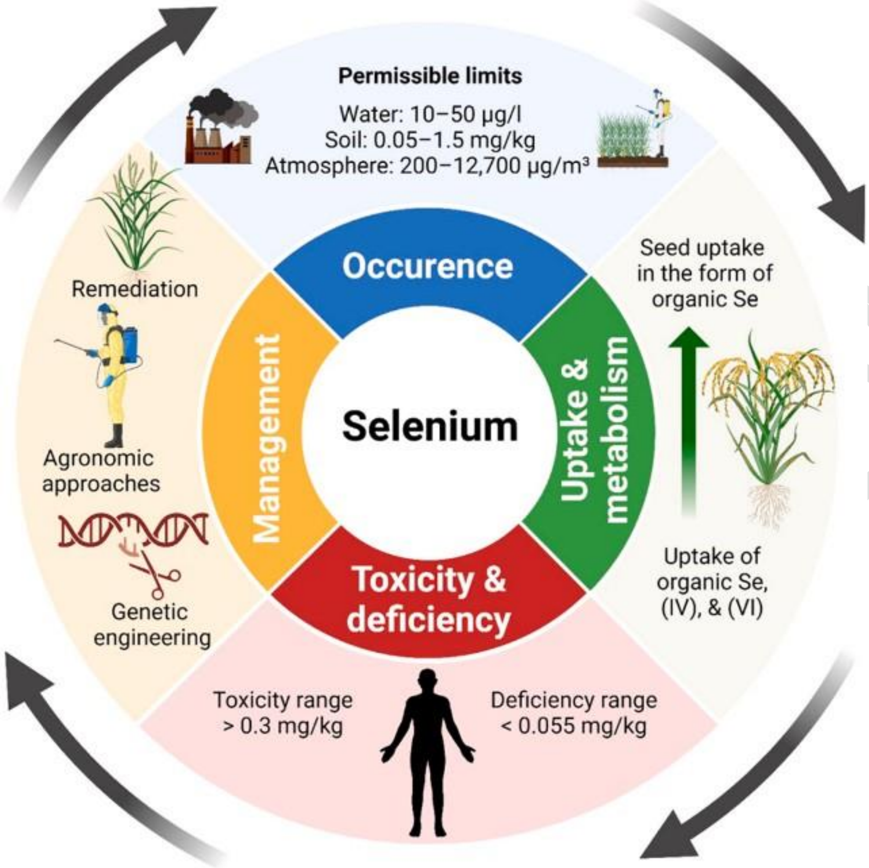
Review Article

“POSSIBILITY OF BIOFORTIFICATION BY SELENIUM FOR ABIOTIC STRESS MANAGEMENT USING EFFECTIVE MICROORGANISMS”

ABSTRACT

Selenium biofortification in crops is to either raise the amount of selenium that accumulates in edible plants or boost their bioavailability. It is among the solutions for the growing worldwide hidden hunger for vital micronutrients. Plant growth promoting rhizobacteria are helpful soil bacteria that live in plant roots and promote plant growth in a variety of ways via diverse methods. Thus, increasing human selenium status depends critically on selenium's mobility across soil, crop, and environmental interfaces. This review covers the importance of selenium for human health, how soil crop systems respond to selenium, how plants use selenium to fend off abiotic stresses, and potential methods for raising selenium concentration through the use of microorganisms (selenorhizobacteria) as biotechnological tools to improve plant nutrition and quality.

GRAPHICAL ABSTRACT



Keywords: Biofortification, Selenium, Abiotic stress, crop improvement

Introduction

The goal of biofortification is to increase the concentration of important micronutrients in edible sections of crops without losing agronomic traits like yield or drought and insect tolerance. This method increases the nutritional value of crops. Biofortification via green technologies, which use microorganisms to enhance soil nutrient status and plant accessibility, and nanotechnology, which applies nanomaterials to plants either alone or in combination with conventional fertilizers (e.g., Zn, Fe, or graphene nanoparticles) (Dhaliwal et al., 2022). The appropriate and healthy existence of humans, animals, archaea, and certain other microbes depends on the mineral micronutrient selenium. (El-Ramady et al., 2014).

The distribution of selenium varies around the world since it is found in the lithosphere layer of the earth's crust, which includes water, soil, and open areas (Hasanuzzaman et al., 2020). The primary source of selenium's role in functioning is its presence in selenium-containing amino acids such selenomethionine (SeMet) and selenocysteine (SeCys).The total selenium concentration of food sources, including chemical forms (speciation), is crucial because it influences the nutritional value and bioavailability of selenium (Kikkert et al., 2013). Benefits derived from biofortifying crops with micronutrients, such as antioxidant qualities that can promote plant growth and protect plants from many forms of abiotic stress. Although selenium is a necessary component of human and animal cells, its significance for plants is still being studied (Jozwiak et al., 2019).

Microorganisms are a novel biotechnological substitute for selenium biofortification since they are crucial to the transformations and availability of selenium. In addition to increasing plant productivity, fertilizing crops with selenium may also improve their nutritional value. The application of conventional agronomic selenium biofortification shows great promise in combating hidden hunger. (Haug et al., 2007).

The amount of selenium applied has a significant impact on its toxicity or benefits (Gupta et al., 2020). Se can activate plants' antioxidant systems at low concentrations, but at large concentrations, it functions as a prooxidant (Nawaz et al., 2015). Se has a number of beneficial impacts on plants, including boosting plant growth, reducing UV-induced oxidative damage, enhancing chlorophyll recovery from light stress, boosting senescing plants' ability to combat oxidative damage, and controlling drought-stricken plants' water status (Yao et al., 2009). Furthermore, Se has the ability to enhance plant growth and development as well as boost the plants' ability to withstand environmental stressors and produce antioxidants (Iqbal et al., 2015), hence contributing to increased grain yields (Hasanuzzaman et al., 2014). Research has shown that selenium (Se) can enhance plant development by fortifying stress tolerance mechanisms like antioxidant and secondary metabolite metabolism. (Kamran et al., 2020). This review will therefore attempt to spread more light to find out the ways for biofortification of crops to increase their tolerance towards drought and can produce reliable yield.

Significance of selenium in human health

Selenium is an amino acid that is part of selenocysteine, an enzyme active site component, and is therefore required in trace amounts by both humans and animals. Se takes responsibility for a variety of metabolic activities in both animal and human systems. Se activates immune cells such natural killer (NK), cytotoxic T, and helper T in the immunological system (Razaghi et al., 2021).

A vital trace element, selenium is fundamentally important for human health. For both humans and animals, selenium is an important mineral with antioxidant qualities (Jezek et al., 2012). Selenium deficiencies in the human body can result in or cause illnesses like Keshan and Kashin-Beck disorders (Fairweathe et al., 2011). Additionally, a shortage in selenium is linked to immune system enhancement, muscular necrosis, hypothyroidism, cardio-cerebrovascular illness, male infertility, and an increased prevalence of several cancers (Fordyce et al., 2013). Se deficiency is thought to be associated with illnesses including acquired immune deficiency syndrome (AIDS) and coronavirus disease 2019 (COVID-19) (Zhang et al., 2020). A vital component of selenoproteins, selenium is involved in numerous biological processes with antioxidant qualities, including defense against free radical damage, thyroid hormone production, DNA synthesis, fertility and reproduction, HIV treatment, and defense against toxic heavy metals (Fairweather-Tait et al., 2011).

This metalloid's predicted significance stems from its association with selenoenzymes, including glutathione peroxidase, thioredoxin reductases, and proteins whose roles are unclear but which contribute to preserving the redox potential of cells (Ramos et al., 2010), as well as additional bodily structure and metabolic processes. A diet deficient in selenium can have a detrimental effect on human health by increasing the risk of heart disease, hypothyroidism, lower male fertility, impaired immune systems, and increased susceptibility to infections and malignancies (Hatfield et al., 2014). Numerous studies have demonstrated the protective effects of selenium compounds, such as SeMet, in the human diet against malignancies of the breast, prostate, lung, bladder, and liver (Fairweather-Tait et al., 2011). Thus, one practical way to lessen the issue of selenium insufficiency in humans and animals is to increase the content of selenium in food crops.

An approximate adequate daily intake of selenium for humans is 50–60 μg, however hazardous levels of selenium ingestion range from 350–700 μg (Badmaev et al., 2018).

It is possible for many microbes to transform inorganic selenite into organic forms, which are thought to be more effective and safe dietary sources of selenium. Additionally, selenium can bind to different polysaccharides and proteins to form complexes. The prevention of cancer and cardiovascular disease is one of the main health benefits of selenium supplementation or ingestion in humans, even at low dosages. Significant increases in the amount of starch, reducing sugars, sulfur-containing amino acids, and other components are involved in selenium augmentation in cereals.

The percentage of people suffering from non-communicable, dietary-dependent illnesses such obesity, hypertension, hyperinsulinemia, insulin resistance, and dyslipidemia is continuously rising (World health statistics, 2020). However, consuming too much selenium can also lead to the development of hypotension, tachycardia, tremor, muscle contractions, hair loss, and lesions on the skin and nails. Therefore, it's important to maintain a balanced daily intake of Se (Hossain et al., 2021). The amount of Se that is advised to be consumed each day varies based on factors like age, gender, stage of pregnancy, length of lactation, region, and food. In addition, the WHO's recommended daily intake of selenium (Se) is trending upward (Table 1). The body mostly absorbs selenium through diet. Products derived from plants and animals contain the trace element.

Table1.: Recommended daily intake levels of Se

country	Men mg/day	Women mg/day	Pregnancy mg/day	Lactation period mg/day	Maximum allowable level mg/day	Toxic dose mg/day	Reference
WHO	42 (1996); 34 (2004); 55 (2019)	39 (1996); 26 (2004); 55 (2019)	57-59	64-71	400	900	Kieliszek et al., 2019
Russia	70	55	55	55	-	-	World Health Organization; 2017
United Kingdom	75	60	-	-	400	-	Kieliszek et al., 2019
United States	55	55	60	70	200	400	The National Academy Press, 2000.
Europe	60	53	-	-	400	-	Commission Directive 2008
India	55	55	60	70	200	-	Alexander et al., 2020

Status of selenium in soil and crop

The physical, chemical, and biological characteristics of the soil have a significant impact on the effectiveness of selenium-treated crops in terms of yield (Zhao et al., 2005). The majority of soils have extremely low bioavailability of selenium content, ranging from 0.01 to 2 mg/kg on average (0.4 mg/kg); nevertheless, in select seleniferous locations, greater amounts of up to 1200 mg/kg have been reported (Fordyce et al., 2005). Selenium concentrations in vegetation on most soils are less than 1 mg/kg. Most plant species on seleniferous soils have a selenium content of 1–

10 mg/kg, while plants that are hyper accumulators of selenium, such as Astragalus and Stanleya genera, can collect 1000–15000 mg/kg at low soil concentrations.

In India, the soil of Gujarat has a very low selenium status and is regarded as deficient in the element; the total amount of selenium in the soil ranges from 0.142 to 0.678 mg/kg, with an average of 0.375 mg/kg (Patel et al., 1970). In agroecosystems, selenium can be present in both inorganic and organic forms. Elemental selenium, selenide, selenite, and selenate are the four oxidation states of inorganic selenium. Uneven distribution of selenium in the soil might result in selenium insufficiency. Low quantities of plant-available forms of selenium in soil can reduce the amount of selenium consumed through food due to crops' slow uptake of the mineral (Winkel et al., 2015). Only around 5% of the selenium that is added to the soil is used by plants. Plant species differ widely in their capacity for selenium buildup in their tissues (White, 2016). In general, SeO_4^{2-} and SeO_3^{2-}have a strong affinity for plants. Conversely, some organic forms of selenium, such as selenocysteine (Se-Cys) and selenomethionine (Se-Met), are employed as active ingredients because they have a higher phytoavailability.

The amount of selenium in the soil and the concentration of selenium in grown food plants in a given area determine the selenium status and intake in a given human population. Therefore, controlling the amount of Se in plants is a major way to manage human intake of Se and its status, which is also influenced by soil Se level, bioaccumulation of Se, and the effectiveness of soil microbes (Stoffaneller and Morse, 2015; Winkel et al., 2015). The average selenium content of soils worldwide ranges from 0.1 to 0.7 mg kg^{-1}. Clay soils typically have an average Se content of 0.8 to 2 mg kg^{-1}, whereas tropical soils have an average Se level of 2-4.5 mg kg^{-1}. As a result, clay soils contain more Se than soils with coarse minerals. (Hartikainen, 2005). Rainfall, organic matter, and soil texture all affect the amount of selenium present in the soil (El-Ramady et al., 2016).

Se content is extremely low in igneous rocks and explosive soils. These kinds of soils are found in hilly nations like Sweden, Finland, and Scotland. Se is abundant in sedimentary rocks. Se is typically prevalent in rocks found in the world's arid regions. These rocks are linked to the detrimental effects of selenium on animals. (McNeal and Balistrieri, 1989; Gupta and Gupta, 2000). By using microorganisms that can metabolize inorganic selenium and be used as seed inoculants or as biotechnological tools for crop nutrition and quality, it may be possible to reduce the complexity of selenium behavior in plants and soils, particularly in soils that are specifically deficient in the mineral. A novel biotechnological approach to address the toxicity and selenium deficit in some agroecosystems could involve combining biofortification and bioremediation (Acuna et al., 2013).

The distribution, mobility, and bioavailability of selenium in soils are significantly impacted by the presence of microbes in the surrounding environment. The bioprocesses involved in the metabolism of bacteria also affect the relative amounts of selenium oxidation states and selenium compounds in the atmosphere. For the purpose of bioremediation of contaminated soils, sediments, industrial effluents, and agricultural drainage waters, bacteria have the capacity to convert inorganic selenium into elemental forms (Dungan et al., 2003). Nearly 80% of the world's total Se reserves are distributed across Australia, Peru, China, the United States, Chile, Canada, New Guinea, Zambia, the Philippines, and Zaire (Liu et al., 2011). There are places in about forty countries where human selenium intake is 10% μg day^{-1} or even significantly lower, while soil selenium concentrations are limited. Conversely, Switzerland, New Zealand, Australia, Finland, and South Korea are among the nations with Se-abundant to Se-limited areas. (Wu et al., 2015).

Total Se concentration ranged from 0.023 to 4.91 mg kg^{-1} in 0–15 cm surface soil and 0.64–515.0 mg kg^{-1} in vegetation samples in the northwest region of Indian soil (Dhillon et al., 2014). Plants, soils, rocks, and groundwater are all parts of the agroecosystem that contain selenium. The range of selenium amounts in animal diets for both adequacy and toxicity is 0.05–0.10 mg kg^{-1} and 4.0–5.0 mg kg^{-1}, respectively (Zanetti et al., 2015).

Role of soil microbes in mobilization of selenium

Enhancing selenium biofortification through crop-microorganism interactions is the focus of this emerging field of study. Plant growth promoting bacteria (PGPB) are a diverse group of soil bacteria that, when coexisting with a host plant, stimulate the host's growth. Nowadays, using bacteria that promote plant growth can serve as an alternative to conventional techniques for improving plants' uptake of micronutrients. (Mora et al., 2015).

It is widely acknowledged that a large range of bacterial species exist in the rhizosphere and that these species perform vital roles in agriculture, including nutrition, plant growth, and disease prevention (Hawkesford et al., 2007). Similar to this, microbes are crucial to the biogeochemical cycle of selenium in the natural world (Ike et al., 2000). Selenium is modified during bacterial metabolism by a variety of processes (oxidation, reduction, or methylation), as well as by selenium respiration in bacteria that are tolerant of selenium and linked to the processes of assimilation and metabolization of this metalloid within the cells. This has demonstrated a great deal of promise for usage in selenium-contaminated sites bioremediation and phytoremediation (Ghosh et al., 2008; Tong et al., 2014). The amount of accessible EXC-Se and SOL-Se in soil and plants was considerably enhanced by the selenium-oxidizing bacteria *Dyella* sp. LX-1, *Rhodanobacterium* sp. LX-100, and *Agrobacterium* sp. T3F4, Concentrations of Se (Guo et al., 2024). Excessive levels of heavy metals, such Cd, in seleniferous soils need to be addressed, despite the fact that microbial selenium fortification in crops is an environmentally beneficial biotechnology (Jiao et al., 2022)

In both aquatic and terrestrial ecosystems, specific bacterial species are crucial for the transformation of selenium. Se serves as the terminal acceptor for the anaerobes' respiration.

Thauera selenatis, which was found in a bioreactor containing Se-oxyanion and agricultural wastewater in California, and *Sulfurospirillum barnesii*, which was found in drainage containing Se, are the first microbes to be isolated to use SeO_4^{2-} for such a process (Macy et al. 1993; Oremland et al. 1994).While SeO_4^{2-} is produced in small quantities, autotrophic bacteria like *Bacillus megaterium* typically oxidize Se^0 into SeO_3^{2-}. Previous investigations into soils and slurries have demonstrated that the oxidation process of Se^0 results in the formation of $SeO_4{}^{2-}$ and $SeO_3{}^{2-}$, respectively (Dowdle and Oremland 1998). A number of other microbial species, such as *Shewanella*, *Anaeromyxobacter dehalogenans*, *Desulfitobacterium sp. D. chlororespirans, Geobacter sulfurreducens,* and *Enterobacter cloacae* etc. were furthermore examined for their capacity to reduce, specifically for conversions from $SeO_3{}^{2-}$ & $SeO_4{}^{2-}$ into Se^0, respectively (Schilling et al. 2020).

Se-metabolising bacteria

Selenate-metabolising bacteria

Bacteria that consume selenium undergo reduction of SeO_4^{2-} in two primary stages: first, selenium reductases convert SeO_4^{2-} into SeO_3^{2-}, and then they further reduce selenite into Se^0.

$SeO_4{}^{2} + 2e + 2H^+ \rightarrow SeO_3{}^{2} + H_2O$

$SeO3^{2} + 4e + 6H^+ \rightarrow Se^0 + 3H_2O$

Microbes such as *B. selenatarsenatis* and *E. cloacae* are capable of undergoing these kinds of reactions, which take place in the presence of anaerobic and aerobic circumstances. That are often engaged in the reduction of SeO_4^{2-} (Nancharaiah and Lens 2015). SerABC selenate reductase is a trimeric molybdenum enzyme that aids in the reduction of SeO_4^{2-} into SeO_3^{2-} in the periplasm.

However, the purest form of selenate reductase enzyme was identified, screened, characterized, and purified by Schroder et al. (1997). The unique way that selenium-metabolizing bacteria operate allows them to break down selenium inside their cells.

Selenite-metabolising bacteria

Many different microbial strains reduce SeO_3^{2-}, contributing up approximately 43% of the soil microbial population that takes part in the conversion of SeO_3^{2-} and SeO_4^{2-} into Se^0. Additionally, anaerobic respiration or detoxification both promote this process (Sura-de Jong 2015). Different bacterial strains that reduce SeO_4^{2-} also exhibit the capacity to dissimilatory reduce SeO_3^{2-}, which mostly promotes the synthesis of lactate and acetate, respectively (Oremland et al. 1994).

The following reactions involve the conversion of SeO_3^{2-} into Se^0:

$C_2H_4OHCOO^- + SeO_2^{-3} + H^+ \rightarrow CH_3COO^- + Se^0 + HCO^{-3} + H_2O$

$C_2H_4OHCOO^- + SeO_2^{-3} + H_2 + 2H^+ \rightarrow CH_3COO^- + Se^0 + 3H_2O$

This is successfully aid in the detoxification mechanism by mediating the process of SeO_3^{2-} reduction in bacteria, which typically occurs in the cytoplasm or periplasm and is then translocated to the cell exterior as Se^0 (Kessi and Hanselmann 2004). Additionally, the reduction of SeO_3^{2-} using organic carbon (lactate, propionate, butyrate, and acetate) with the help of *Cronobacter sp*. has been demonstrated. In this case, organic carbon acts as an electron donor in the microaerobic environment where microorganisms require oxygen to completely decrease SeO_3^{2-} (Estrada et al. 2020). Therefore, all of these bacterial strains can be investigated for their ability to convert inorganic forms of selenium and for use as a source of selenium supplement in food. Potential biotechnological uses for PGPR include serving as a carrier for agricultural biofortification. The selenium linked with the bacterial inoculum may be incorporated and translocated into leaves and other plant parts by plants treated with bacteria that were tolerant of selenium.

This bacterial inoculum enhanced with selenium can be employed as a biotechnological instrument for plant selenium biofortification.Wheat plant tissue had higher selenium concentrations after being inoculated with selenium-enriched rhizobacteria, or seleniorhizobacteria, which can metabolize selenium (Acuna et al., 2013). The selenium content of grain was enhanced in plants co-inoculated with a combination of *selenibacteria* strains and *G.*

claroideum. A potential substitute for increasing the selenium content of cereals cultivated on soils poor in selenium is the use of microorganisms that are tolerant of selenium.

Many research investigations have demonstrated a variety of aerobic bacteria that are resistant of selenium, including *Pseudomonas aeruginosa, Bacillus sp., Stenotrophomonas sp., Acinetobacter sp., and Klebsiella sp.* (Acuna et al., 2013) etc. possess the capacity to accumulate selenium, and these bacteria may be employed as inoculants to enhance cereal wheat with selenium (Table 2).

Table 2.: Plant growth promoting bacteria used for selenium biofortification in crops.

No	Microorganisms	Plant	Method of fertilization	Source of Se	Results	References
1.	*Enterobacter* sp. B16, *Stenotrophomonas* sp. B19	Triticum aestivum L. cv. Fritz	Inoculation Root	Selenobacteria	Enhanced selenium content in Shoot	Acuna et al. (2013)
2.	*Bacillus* sp. R8, *Enterobacter* sp. B16, *Pseudomonas* sp. R12, *Stenotrophomonas* sp. B19	Triticum aestivum L. cv. Puelche	Inoculation Root	Selenobacteria	Enhanced selenium content in Grain	Duran et al. (2013)
3.	*Bacillus* sp. YAM2	Triticum aestivum L.	Seed palletization	Selenobacteria	Enhanced selenium content in wheat kernels & stems	Yasin et al. (2015)
4.	*Acinetobacter* sp. E6. 1, *Bacillus* sp. R8, *Klebsiella* sp. E2	Triticum aestivum L. cv.	Seed palletization	Endophytic Selenobacteria	Enhanced selenium content in Shoot	Duran et al. (2015)

Selenium biofortification mediated by micro-organisms for effective and sustainable crop production

Microbes help with Se-biofortification, which raises crop nutrient levels and uses them as fertilizer for both biotechnological and conventional breeding techniques. In areas where soil nutrients are scarce, this procedure improves the nutritional content of crops (Hossain et al. 2021). Additionally, in Se-deficient soils, Se-biofortification is carried out by choosing a plant species that can better absorb micronutrients through their edible organs, enhancing the diets of humans and animals.The most effective method for ensuring that plants absorb selenium is through biofortification, which allows diverse agricultural soils deficient in selenium to recoup it through animal excrement as well (Ye et al. 2020). Certain microorganisms help plants absorb nutrients more efficiently, and in addition to increase plant growth and productivity, these microbes also assist plants resist stress. Microflora, including endophytic fungi, mycorrhizae, and rhizobacteria that promote plant growth, are being employed in biofortification processes. (Hossain et al. 2021). Mycorrhizae act as intermediaries. Plant uptake of selenium (Se) improved the uptake and accumulation of selenium and selenite, especially in *Glomus versiform* and *Funneliformis sp.* (Patel et al., 2018), (**Table 3)**

Table 3.: Microbes mediating Se-biofortification for sustainable agricultural practices

S.No.	**Micro-organism**	**Plant species**	**References**
1.	*Acinetobacter* sp.	*Triticum aestivum*	Duran et al. (2013)
2.	*Alcaligenes faecalis, Paraburkholderiame gapolitana,*	*Ricinus communis, Glycine max*	Trivedi et al. (2020)
3.	*Anabaena* sp.	*Triticum aestivum*	Abadin et al. (2017)
4.	*Bacillus amyloliquefaciens*	*Arabidopsis thaliana*	Wang et al. (2017)
5.	*Bacillus axarquiens*	*Triticum aestivum*	Duran et al. (2013)
6.	*Bacillus cereus*	*Triticum aestivum*	Yasin et al. (2015)
7.	*Glomus fasciculatum*	*Allium sativum*	Patharajan and Raaman (2012)
8.	*Glomus irtraradices*	*Allium sativum*	Larsen et al. (2006)
9.	*Rhizophagus intraradices*	*Lactuca sativa, Asparagus officinalis, Lac-tuca sativa, Allium cepa*	Sanmartin et al. (2018)
10.	*Glomus versiform*	*Triticum aestivum*	Luo et al. (2019)
11.	*Glomus mosseae*	*Lolium perenne, Allium sativum, Medicago sativa, Glycine max, Zea mays*	Patharajan and Raaman (2012); Yu et al.(2011)
12.	*Trichoderma harzianum*	*Allium cepa*	Sanmartin et al. (2018)
13.	*Alternaria seleniiphila, Alternaria astragali,Aspergillus leporis, Fusarium acuminatum*	*Stanleya pinnata, Astragalus bisulcatus, Stanleya pinnata, Astragalus racemosus*	Lindblom et al. (2013)

14.	*Bacillus* sp. R12, *Enterobacter* sp. B16, *Pseudomnas* sp. R8, *Stenotrophomonas* sp. B19	*Triticum aestivum*	Duran et al. (2013)
15.	*Bacillus subtilis*	*Allium cepa*	Golubkina et al. (2019)
16.	*Bacillus licheniformis, Bacillus pichinotyi*	*Triticum aestivum*	Yasin et al. (2015)
17.	*Bacillus mycoides*	*Brassica juncea*	Lampis et al. (2009)
18.	*Bacillus* sp. E6.1, *Enterobacter ludwigii,Klebsiella oxytoca*	*Triticum aestivum*	Duran et al. (2014)
19.	*Calothrix sp.] Providencia* sp.	*Triticum aestivum*	Rana et al. (2012); Yasin et al. (2017)
20.	*Rhizobium* sp.	*Astragalus bisulcatus, A. drummondii*	Alford et al. (2014)
21.	*Stenotrophomonas maltophilia*	*Ricinus communis, Glycine max, Brassica juncea*	Businelli et al., (2015)

Abiotic stress management by selenium

In crops, selenium's function in reducing environmental stress has been widely documented. At modest concentrations, selenium can promote plant development and help plants adapt to a variety of environmental stressors, including abiotic stressors like drought, cold, and heavy metal stress (Oancea et al., 2015; Mora et al., 2015; Handa et al., 2016). Plants may grow and develop to their full potential if selenium levels in the soil are raised during stressful times (Sieprawska et al., 2015). Increased water retention in plant tissue may result from selenium stimulation's rise in the contents of both organic and non-organic osmo-protectants (Hajiboland et al., 2015). It was widely accepted that adding selenium lessens these pressures' detrimental effects on plants' and fruits' ability to produce biomass (Xue et al., 2001).

The activation of antioxidative enzymes by selenium in appropriate amounts helps modulate oxidative stress (Hartikainen et al., 2000). Three mechanisms exist by which selenium can control the amounts of reactive oxidative species (ROS) in stressed plants: (1) by stimulating the O^{2-} spontaneous dismutation into H_2O_2; (2) by a direct interaction between molecules containing selenium and ROS; (3) by regulating the activity of antioxidant enzymes. One important way that selenium may help plants avoid stress is by controlling the amount of ROS they produce. Plant cells produce very little ROS under normal circumstances. Stress conditions like as drought, excessive water, intense light, cold, salt, and heavy metals, on the other hand, can cause a buildup or increase in ROS levels in plants. An increase in ROS generation can be harmful to plants. The primary types of ROS are singlet oxygen (O_2), hydroxylic free radical (OH), hydrogen peroxide (H_2O_2), superoxide anion (O^{2-}), and methyl radical (CH_3).When plants are exposed to various environmental stressors, a small amount of selenium added to the growth substrates can lower the excess ROS formation (Cartes et al., 2010).

Selenium can be added to stressed plants to increase their antioxidant levels, which will control the amount of reactive oxygen species. In order to counteract the increased ROS levels, plants typically activate two different forms of antioxidants. Low molecular weight compounds like glutathione and ascorbic acid are one type of antioxidant; enzymes such as superoxide dismutase, peroxidase, catalase, ascorbate peroxidase, glutathione reductase, and glutathione peroxidase are another type of antioxidant (Hartikainen et al., 2000). These antioxidants have the ability to interact with ROS directly or indirectly through the activity of enzymes. Selenium has the ability to directly or indirectly regulate the synthesis and scavenging of reactive oxygen species (ROS) by modulating antioxidant levels. It is generally known that glutathione and selenium can combine directly to create selenocysteine, selenio-methionine, and eventually proteins that contain selenium (Terry et al., 2000).

The mechanism behind this beneficial effect of selenium on antioxidant capacity could be either indirect—caused by selenium-induced activation of general stress resistance mechanisms—or direct—caused by the antioxidant activity of selenio-compounds. Additionally, adequate selenium levels can shield plants from the harm that heavy metals like As, Hg, Pb, Cd, Zn, Cu, and

Cr can inflict (Malik et al., 2012). Selenium may limit the uptake and translocation of heavy metals from plant roots, which could be a relevant heavy metal detoxification process.

Selenium for crop yield improvement

Many studies have been conducted to ascertain the advantageous function of Se in enhancing yield (Broadley et al., 2010; Ekanayake et al., 2015; Nawaz et al., 2016). Studies on the effects of selenium (Se), including fertilizer, foliar spraying, and nanoparticles, on crop yield enhancement. Under drought stress, exogenous Se-foliar spray (40 mg L−1) boosted the crude protein by 47%, fiber synthesis by 10%, and Se contents by 36% without changing the crude ash contents (Nawaz et al., 2016). Ekanayake et al. (2015) examined the effects of field-applied selenium (30 g ha^{-1} of $SeO3^{2-}$ and $SeO4^{2-}$) on the production of lentil grains at the 50% flowering and seedling phases. The production of lentil seeds increased by 10 and 4%, respectively, upon the use of these fertilizers. Sweet corn's response to exogenous Se spray has been reported by Huang et al. (2019). A spray applied at different growth stages with different doses of Se fertilizer (0.80–1.00 g Se L^{-1}) increased the sugar content and had a beneficial influence on seed production.

Recent reports describe the application of Se nanoparticles to increase crop output. Hernandez-Hernandez et al. (2019) shown that utilizing 10 mg L^{-1} of Se nanoparticles increased tomato yield by 21%. Additionally, vitamin C, GSH, flavonoid levels, firmness, total soluble solids (TSS), and fruit acidity were all improved by the selenium treatment. In addition, Zahedi et al. (2019b) showed how Se (Na2SeO4) foliar spray and Se nanoparticles affected various pomegranate growth indices. Applications made in tandem significantly enhanced yield, peel diameter, and fruit count.

Improvement of crop quality by selenium biofortification

Enhancing the essential nutritional content in edible portions of plants, animals, or microorganisms using agronomic or biotechnological processes is known as biofortification. To mitigate micronutrient deficiencies, agronomic biofortification is a simple, effective, and environmentally friendly method (Yuan et al., 2012). The best way to enrich crops with this element is one of the most important aspects of Se biofortification. Selenium can be sprayed on the foliage, added to mineral fertilizers, or mixed into the nutrient medium in hydroponic farming. (Hawrylak-Nowak, 2013; Banuelos et al., 2017; Golubkina et al., 2018). The efficiency, simplicity, and lack of multidirectional chemical changes of selenium in the soil, along with its limited translocation to aboveground organs, appear to be the benefits of applying selenium topically over soil application. There seems to be less of a risk of environmental pollution because the foliar spray requires a minimal consumption of Se salts (Puccinelli et al., 2017; Hawrylak-Nowak et al., 2018c).

The foliar application of Se has an advantage over the other methods, according to a recent study by Motesharezadeh et al. (2020) on alfalfa grown in calcareous and non-calcareous soils supplied with Se (Se soil application, selenobacteria inoculation, Se foliar application, combined soil and foliar Se application). Additionally, they proposed that a natural way of enhancing the quality of alfalfa feed could be by the inoculation of plants with selenobacteria. In a closed soilless system, Pannico et al. (2019) found that Se treatments (8–40 μM as SO_4^{2-}) decreased the production of green butterhead lettuce (FW), while yield reduction in the red cultivar was noted at ≥32 μM Se. Significantly, both cultivars showed a rise in the foliar Se content; however, the red butterhead lettuce absorbed around 57% more Se than the green one. Further, the red cultivar's carotenoid content increased with 32 μM Se, while the phenolic acid and anthocyanin contents increased with 16 μM Se.

Selecting the appropriate type of selenium (Se) is essential for successful biofortification. The majority of research has shown that SeO_4^{2-} is a more effective form than SeO_3^{2-} for foliar and soil treatment. (Lyons, 2018). Wang et al. (2020) reported that the uptake of inorganic selenium from foliar spray was found to be more efficient than that of its organic forms. Additionally, the phloem was found to transport tiny amounts (less than 10%) of selenium deposited in the shoots to other organs. On the other hand, organic Se was absorbed by the roots at a significantly higher rate than inorganic Se. The most significant selenium uptake and translocation by the xylem and phloem was brought about by the application of selenium methyl cysteine. In four rice cultivars, Lidon et al. (2019) observed that foliar SeO_3^{2-} fertilization increased grain Se content by 427–884 times, whereas SeO_4^{2-} treatment increased grain Se concentrations by 128–347 times.

In addition to raising the concentration of Se in the rice grains, the foliar application of Se also enhanced the concentration of other bioactive compounds. Lidon et al. (2018) supplied various rice genotypes with 30–300 g Se ha^{-1} as SeO_3^{2-} or SeO_4^{2-} in a previous agronomic biofortification study. Both Se forms induced an increase in total lipids (particularly oleic, linoleic, and palmitic acids), sugars, and proteins; however, the macronutrient content of the rice flour varied within the rice genotypes. Se malnutrition may be effectively decreased in Se-deficient areas by raising the Se content of cereals (rice and wheat) using a process known as Se biofortification. The application of 10 g Se ha^{-1} boosted the Se content of wheat grain in the UK by up to 10 times, according to research by Broadley et al. (2010). Another potential method of Se-biofortification is the use of arbuscular mycorrhizal fungi (AMF) (Golubkina et al., 2020).

Concluding remarks and future direction

A safe and economical way to meet this goal in areas lacking in selenium is to apply pelleted seeds containing microorganisms (selenorhizobacteria) to the soil or rhizosphere. This will stimulate natural processes that improve nutrient uptake, productivity, abiotic stress tolerance, and crop quality. Utilizing selenium-tolerant bacteria (selenorhizobacteria) in biotechnological applications is a viable approach to selenium biofortification. Further investigation is necessary to identify the selenium forms found in grains as well as the genetic and biochemical pathways that underlie the biofortification of plants with selenium in order to develop innovative technologies for selenium biofortification initiatives.

Therefore, management techniques should concentrate on building a link between agricultural enriched food products, selenium concentration, and bioavailability in soil in order to minimize selenium shortage and associated diet related disruptions by the plant growth boosting bacteria. The fundamental mechanisms of selenium uptake, distribution, and metabolism, as well as any favorable or detrimental effects on plant physiology and plant performance under abiotic stressors, have all been covered in this study.

Additionally, we proposed the biofortification topic. At low quantities, selenium has positive impacts on plant growth and development. Furthermore, it has been documented that both hyperaccumulator and non-hyperaccumulator plants benefit from growth effects associated with the ideal Se concentration. Whether Se is a necessary plant nutrient or not is still up for debate. For superior plant performance brought about by the administration of Se, the ideal dose of Se should be determined for each species of plant, as well as for each development stage, size, growth substrate, application method, form, and—above all—the concentration of Se in the tissue. Se can effectively increase tolerance to a variety of abiotic stressors, as demonstrated by a substantial body of experimental data, which calls for further, in-depth research. Furthermore, just a few crops have been researched in this area, although Se has potential as a biofortification or phytofortification agent enhancing the nutritional quality of meals. The synthesis of non-specific Seproteins, pro-oxidative creation of ROS, and oxidative stress, which impede physiological functions, have been linked to selenium phytotoxicity. It boosts the creation of reactive oxygen species (ROS) because it is a pro-oxidant; nevertheless, it has been shown that a modest amount of selenium (Se) can upregulate the antioxidant defense system, which is an intriguing area of research. The results of the study showed that selenite resistance is regulated by ethylene and jasmonate acid signaling. Plant growth and development under both normal and stress conditions are thought to be influenced by the interplay between phytohormones and selenium (Se), which in turn regulates genes involved in Se production, uptake, and assimilation. (Tamaoki et al., 2008;

Van Hoewyk et al., 2008; Freeman et al., 2010; Wang et al., 2018). The study should be expanded to take into account various growth environments, both in the lab and in the field, and to use a variety of grown plants as test plants. It is important to extensively utilize omics technologies, such as transcriptomics, proteomics, metabolomics, and genomics, in various plant species to determine the mechanism of selenium's presence as a beneficial or harmful component. Furthermore, the engineering of Se-mediated metabolic pathways can help identify the true mechanism behind Se-mediated stress tolerance and offer fresh perspectives on current understanding.

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3.

References

Acuna, et al., 2013. Selenobacteria selected from the rhizosphere as a potential tool for Se biofortification of wheat crops. Biol. Fertil. Soils 49 (2), 175–185.

Alford ER, Lindblom SD, Pittarello M, Freeman JL, Fakra SC, Marcus MA, Broeckling C, Pilon-Smits EA, Paschke MW (2014) Roles of rhizobial symbionts in selenium hyperaccumulation in *Astragalus* (Fabaceae). Am J Bot 101(11):1895–1905

Badmaev et al., 2018. What is Recommended Daily Dose of Selenium Supplement and What Form of Supplemental Selenium is Recommended?.

Banuelos, G.S., Lin, Z.-Q., Broadley, M., 2017. Selenium biofortification. In: Pilon-Smits, E.A.H., Winkel, L.H.E., Lin, Z.-Q. (Eds.), Selenium in Plants. Plant Ecophysiology. Springer International Publishing AG, Cham, pp. 231–255.

Broadley, M.R., Alcock, J., Alford, J., Cartwright, P., Foot, I., Fairweather-Tait, S.J., et al., 2010. Selenium biofortification of high-yielding winter wheat (*Triticum aestivum* L.) by liquid or granular Se fertilisation. Plant Soil 332 (1–2), 5–18.

Broadley, M.R., Alcock, J., Alford, J., Cartwright, P., Foot, I., Fairweather-Tait, S.J., et al., 2010. Selenium biofortification of high-yielding winter wheat (*Triticum aestivum* L.) by liquid or granular Se fertilisation. Plant Soil 332 (1–2), 5–18.

Businelli D, D’Amato R, Onofri A, Tedeschini E, Tei F (2015) Seenrichment of cucumber (*Cucumis sativus* L.), lettuce (*Lactuca sativa* L.) and tomato (*Solanum lycopersicum* L. Karst) through fortification in pre-transplanting. Sci Hortic 197:697–704

Cartes, et al., 2010. Selenium improves the antioxidant ability against aluminium induced oxidative stress in ryegrass roots. Ann. Appl. Biol. 156 (2), 297–307.

Commission Directive 2008/100/EC of 28 October 2008 amending Council Directive 90/496/EEC on nutrition labeling for foodstuffs as regards recommended daily allowances, energy conversion factors and definitions. Official Journal of the European Union. 2008;51:9–12.

Dhaliwal, S.S., Sharma, V., Shukla, A.K., Verma, V., Kaur, M., Shivay, Y.S., Nisar, S., Gaber, A., Brestic, M., Barek, V., 2022. Biofortification—a frontier novel approach to enrich micronutrients in field crops to encounter the nutritional security. Molecules 27 (4), 1340. https://doi.org/10.3390/molecules27041340.

Dhillon, K.S. and Dhillon, S.K., 2014. Development and mapping of seleniferous soils in northwestern India. *Chemosphere*, *99*, pp.56-63.

Dowdle PR, Oremland RS (1998) Microbial oxidation of elemental selenium in soil slurries and bacterial cultures. Environ Sci Technol 32(23):3749–3755.

Dungan, et al., 2003. Transformation of selenate and selenite by Stenotrophomonas maltophilia isolated from a seleniferous agricultural drainage pond sediment. Environ. Microbiol. 5 (4), 287–295.

Duran, et al., 2013. Enhanced selenium content in wheat grain by co-inoculation of selenobacteria and arbuscular mycorrhizal fungi: a preliminary study as a potential Se biofortification strategy. J. Cereal Sci. 57 (3), 275–280.

Ekanayake, L.J., Vial, E., Schatz, B., McGee, R., Thavarajah, P., 2015. Selenium fertilization on lentil (*Lens culinaris* Medikus) grain yield, seed selenium concentration, and antioxidant activity. Field Crops Res. 177, 9–14.

El-Ramady, H., Abdalla, N., Taha, H.S., et al., 2016. Selenium and nano-selenium in plant nutrition. Environ. Chem. Lett. 14, 123–147.

El-Ramady, H.; Abdalla, N.; Alshaal, T.; Domokos-Szabolcsy, É.; Elhawat, N.; Prokisch, J.; Sztrik, A.; Fári, M.; El-Marsafawy, S.; Shams, M.S. Selenium in soils under climate change, implication for human health. Environ. Chem. Lett. **2014**, 13, 1–19.

Estrada AM, Olivares LGG, Lopez EC, Serrano GR (2020) SelA and SelD genes involved in selenium absorption metabolism in lactic acid bacteria isolated from Mexican cheeses. Int Dairy J 103:104629.

Fairweather-Tait, et al., 2011. Selenium in human health and disease. Antioxid. Redox Signal. 14 (7), 1337–1383.

Fairweather-Tait, S.J.; Bao, Y.; Broadley, M.R.; Collings, R.; Ford, D.; Hesketh, J.E.; Hurst, R. Selenium in human health and disease. Antioxid. Redox Signal. **2011**, 14, 1337–1383.

Fordyce et al., 2005. Selenium Deficiency and Toxicity in the Environment. In Essentials of Medical Geology: Impacts of the Natural Environment on Public Health, pp. 373–415.

Fordyce, F.M. Selenium deficiency and toxicity in the environment. In Essentials of Medical Geology; Springer: Dordrecht, The Netherlands, 2013; pp. 375–416.

Freeman, J.L., Tamaoki, M., Stushnoff, C., Quinn, C.F., Cappa, J.J., Devonshire, J., et al., 2010. Molecular mechanisms of selenium tolerance and hyperaccumulation in *Stanleya pinnata*. Plant Physiol. 153, 1630–1652.

Ghosh, et al., 2008. Isolation and characterization of selenite- and selenate-tolerant microorganisms from selenium contaminated sites. World J. Microbiol. Biotechnol. 24 (8), 1607–1611.

Golubkina N, Zamana S, Seredin T, Poluboyarinov P, Sokolov S, Baranova H, Krivenkov L, Pietrantonio L, Caruso G (2019) Effect of selenium biofortification and beneficial microorganism inoculation on yield, quality and antioxidant properties of shallot bulbs. Plants 8(4):102

Golubkina, N., Kekina, H., Caruso, G., 2018. Yield, quality and antioxidant properties of Indian mustard (*Brassica juncea* L.) in response to foliar biofortification with selenium and iodine. Plants 7 (4), 80. https://doi.org/10.3390/plants7040080.

Guidelines for drinking-water quality - 4th ed. Geneva: World Health Organization; 2017 г. License: CC BY-NC-SA 3.0 IGO. Available by: http://apps.who.int/iris. (access date: 16.01.2023).

Guo, J., Luo, X., Zhang, Q., Duan, X., Yuan, Y. and Zheng, S., 2024. Contributions of selenium-oxidizing bacteria to selenium biofortification and cadmium bioremediation in a native seleniferous Cd-polluted sandy loam soil. *Ecotoxicology and Environmental Safety*, *272*, p.116081.

Gupta, A.; Rico-Medina, A.; Caño-Delgado, A.I. The physiology of plant responses to drought. Science **2020**, 368, 266–269.

Gupta, U.C., Gupta, S.C., 2000. Selenium in soils and crops, its deficiencies in livestock and humans: implications for management. Commun. Soil Sci. Plant Anal. 31, 1791–1807.

Hajiboland, et al., 2015. Influence of selenium in drought-stressed wheat plants under greenhouse and field conditions. Acta Agric. Slov. 105 (2), 175–191.

Handa, et al., 2016. Selenium: an antioxidative protectant in plants under stress. Plant Metal. Interact.: Emerg. Remediat. Tech. 179–207.

Hartikainen, et al., 2000. Selenium as an anti-oxidant and pro-oxidant in ryegrass. Plant Soil 225 (1), 193–200.

Hartikainen, H., 2005. Biogeochemistry of selenium and its impact on food chain quality and human health. J. Trace Elem. Med. Biol. 18, 309–318.

Hasanuzzaman, M.; Bhuyan, M.H.M.B.; Raza, A.; Hawrylak-Nowak, B.; Matraszek-Gawron, R.; Al Mahmud, J.; Nahar, K.; Fujita,M. Selenium in plants: Boon or bane? Environ. Exp. Bot. **2020**, 178, 104170.

Hasanuzzaman, M.; Nahar, K.; Fujita, M. Silicon and Selenium: Two Vital Trace Elements that Confer Abiotic Stress Tolerance to Plants. Two Vital Trace Elements that Confer Abiotic Stress Tolerance to Plants.; Elsevier Inc.: Amsterdam, The Netherlands, 2014; Volume 1; ISBN 9780128010884.

Hatfield, et al., 2014. Selenium and selenocysteine: roles in cancer, health and development. Trends Biochem. Sci. 39 (3), 112–120.

Haug, et al., 2007. How to use the world's scarce selenium resources efficiently to increase the selenium concentration in food. Microb. Ecol. Health Dis. 19 (4), 209–228.

Hawkesford, et al., 2007. Strategies for increasing the selenium content of wheat. J. Cereal Sci. 46 (3), 282–292.

Hawrylak-Nowak, B., 2013. Comparative effects of selenite and selenate on growth andselenium accumulation in lettuce plants under hydroponic conditions. Plant Growth Regul. 70, 149–157.

Hawrylak-Nowak, B., Hasanuzzaman, M., Matraszek-Gawron, R., 2018c. Mechanisms of selenium-induced enhancement of abiotic stress tolerance in plants. In: Hasanuzzaman, M., Fujita, M., Oku, H., Nahar, K., Hawrylak-Nowak, B. (Eds.), Plant Nutrients and Abiotic Stress Tolerance. Springer, Singapore, pp. 269–295.

Hernandez-Hernandez, H., Quiterio-Gutierrez, T., Cadenas-Pliego, G., et al., 2019. Impact of selenium and copper nanoparticles on yield, antioxidant system, and fruit quality of tomato plants. Plants 8, 355. https://doi.org/10.3390/plants8100355.

Hossain A, Skalicky M, Brestic M, Maitra S, Sarkar S, Ahmad Z, Vemuri H, Garai S, Mondal M, Bhatt R, Kumar P (2021) Selenium biofortification: roles, mechanisms, responses and prospects. Molecules 26(4):881

Hossain A, Skalicky M, Brestic M, Maitra S, Sarkar S, Ahmad Z, Vemuri H, Garai S, Mondal M, Bhatt R, Kumar P (2021) Selenium biofortification: roles, mechanisms, responses and prospects. Molecules 26(4):881

Hossain, A.; Skalicky, M.;Brestic, M.; Maitra, S.; Sarkar, S.;Ahmad, Z.; Vemuri, H.; Garai, S.;Mondal, M.; Bhatt, R.; et al. Selenium Biofortification: Roles, Mechanisms,Responses and Prospects. Molecules. 2021; 26: 881. https://doi.org/10.3390/molecules26040881.

Huang, A.-H., Huang, K.-J., Peng, J., Huang, S., Bi, X.C., Zhai, R., et al., 2019. Effects of foliar spraying of selenium fertilizer on selenium-enriched content, heavy metal content and yield of sweet corn grain. J. South. Agric. 50, 40–44.

Ike, et al., 2000. Selenate reduction by bacteria isolated from aquatic environment free from selenium contamination. Water Res. 34 (11), 3019–3025.

Institute of Medicine. Dietary reference intakes for vitamin C, vitamin E, selemium, and carotenoids. Washington DC. The National Academy Press, 2000.

Iqbal, M.; Hussain, I.; Liaqat, H.; Ashraf, M.A.; Rasheed, R.; Rehman, A.U. Exogenously applied selenium reduces oxidative stress and induces heat tolerance in spring wheat. Plant Physiol. Biochem. **2015**, 94, 95–103.

Jan Alexander, Alexey Tinkov, et al. Early Nutritional Interventions with Zinc, Selenium and Vitamin D for Raising Anti-Viral Resistance. Against Progressive COVID-19. Nutrients 2020; 12: 2358. doi:10.3390/nu12082358.

Jezek et al. 2012. Selenium – An Important Antioxidant in Crops Biofortification.

Jiao, L., Zhang, L., Zhang, Y., Wang, R., Lu, B., Liu, X., 2022. Transcriptome analysis provides new insight into the distribution and transport of selenium and its associated metals in selenium-rich rice. Environ. Pollut. 301, 118980 https://doi.org/10.1016/j.envpol.2022.118980.

Jozwiak,W.; Politycka, B. Effect of selenium on alleviating oxidative stress caused by a water deficit in cucumber roots. Plants

Kamran, M.; Parveen, A.; Ahmar, S.; Malik, Z.; Hussain, S.; Chattha, M.S.; Saleem, M.H.; Adil, M.; Heidari, P.; Chen, J.T. An overview of hazardous impacts of soil salinity in crops, tolerance mechanisms, and amelioration through selenium supplementation. Int. J. Mol. Sci. **2020**, 21, 148.

Kessi J, Hanselmann KW (2004) Similarities between the abiotic reduction of selenite with glutathione and the dissimilatory reaction mediated by *Rhodospirillum rubrum* and *Escherichia coli*. J Biol Chem 279(49):50662–50669.

Kessi J, Hanselmann KW (2004) Similarities between the abiotic reduction of selenite with glutathione and the dissimilatory reaction mediated by *Rhodospirillum rubrum* and *Escherichia coli*. J Biol Chem 279(49):50662–50669

Kieliszek, M. Selenium–Fascinating Microelement, Properties and Sources in Food. Molecules. 2019; 24(7): 1298. https://doi.org/10.3390/molecules24071298.

Kieliszek, M. Selenium–Fascinating Microelement, Properties and Sources in Food. Molecules. 2019; 24(7): 1298. https://doi.org/10.3390/molecules24071298.

Kikkert, et al., 2013. Plant uptake and translocation of inorganic and organic forms of selenium. Arch. Environ. Contam. Toxicol. 65 (3), 458–465.

Lampis S, Ferrari A, Cunha-Queda AC, Alvarenga P, Di Gregorio S, Vallini G (2009) Selenite resistant rhizobacteria stimulate SeO_3^{2}–phytoextraction by *Brassica juncea* in bioaugmented waterfiltering artificial beds. Environ Sci Pollut Res 16(6):663–670

Larsen EH, Lobinski R, Burger-Meyer K, Hansen M, Ruzik R, Mazurowska L, Rasmussen PH, Sloth JJ, Scholten O, Kik C (2006) Uptake and speciation of selenium in garlic cultivated in soil amended with symbiotic fungi (mycorrhiza) and selenate. Analyt Bioanalyt Chem 385(6):1098–1108

Lidon, F.C., Oliveira, K., Galhano, C., Guerra, M., Ribeiro, M.M., Pelica, J., et al., 2019. Selenium biofortification of rice through foliar application with selenite and selenate. Exp. Agric. 55, 528–542.

Lidon, F.C., Oliveira, K., Ribeiro, M.M., Pelica, J., Pataco, I., Ramalho, J.C., et al., 2018. Selenium biofortification of rice grains and implications on macronutrients quality. J. Cereal Sci. 81, 22–29.

Lindblom SD, Valdez-Barillas JR, Fakra SC, Marcus MA, Wangeline AL, Pilon-Smits EA (2013) Influence of microbial associations on selenium localization and speciation in roots of *Astragalus* and *Stanleya* hyperaccumulators. Environ Exp Bot 88:33–42

Liu, Y., Li, F., Yin, X.B., Lin, Z.Q., 2011. Plant-based biofortification: from phytoremediation to Se-enriched agriculture products. In: Sharma, S.K., Mudhoo, A. (Eds.), Green Chemistry for Environmental Sustainability. CRC Press, Boca Raton, FL, pp. 341–356.

Luo W, Li J, Ma X, Niu H, Hou S, Wu F (2019) Effect of arbuscular mycorrhizal fungi on uptake of selenate, selenite, and selenomethionine by roots of winter wheat. Plant Soil 438(1):71–83

Lyons, G., 2018. Biofortification of cereals with foliar selenium and iodine could reduce hypothyroidism. Front. Plant Sci. 9, 730. https://doi.org/10.3389/fpls.2018.00730.

Macy JM, Lawson S, DeMoll-Decker H (1993) Bioremediation of selenium oxyanions in San Joaquin drainage water using *Thauera selenatis* in a biological reactor system. Appl Microbiol Biotechnol 40(4):588–594

Malik, et al., 2012. Selenium antagonises the toxic effects of arsenic on mungbean (Phaseolus aureus Roxb.) plants by restricting its uptake and enhancing the antioxidative and detoxification mechanisms. Environ. Exp. Bot. 77, 242–248.

McNeal, J.M., Balistrieri, L.S., 1989. Geochemistry and occurrence of selenium: an overview. In: Jacobs, L.W. (Ed.), Selenium in Agriculture and the Environment. ACSESS, Madison, WI 53711 USA, pp. 1–13.

Mora, et al., 2015. Improving selenium status in plant nutrition and quality. J. Soil Sci. Plant Nutr. 15 (2), 486–503.

Mora, et al., 2015. Improving selenium status in plant nutrition and quality. J. Soil Sci. Plant Nutr. 15 (2), 486–503.

Motesharezadeh, B., Ghorbani, S., Alikhani, H.A., 2020. The effect of selenium biofortification in alfalfa (*Medicago sativa*). J. Plant Nutr. 43 (2), 240–250.

Nancharaiah YV, Lens PN (2015) Selenium biomineralization for biotechnological applications. Trends Biotechnol 33(6):323–330.

Nawaz, F., Ahmad, R., Ashraf, M., Waraich, E., Khan, S., 2015. Effect of selenium foliar spray on physiological and biochemical processes and chemical constituents of wheat under drought stress. Ecotoxicol. Environ. Saf. 113, 191–200.

Nawaz, F.; Ahmad, R.; Ashraf, M.Y.; Waraich, E.A.; Khan, S.Z. Effect of selenium foliar spray on physiological and biochemical processes and chemical constituents of wheat under drought stress. Ecotoxicol. Environ. Saf. **2015**, 113, 191–200.

Oancea, et al., 2015. Development of a new technology for protective biofortification with selenium of brassica crops. AgroLife Sci. J. 4 (2), 80–85.

Oremland RS, Blum JS, Culbertson CW, Visscher PT, Miller LG, Dowdle P, Strohmaier FE (1994) Isolation, growth, and metabolism of an obligately anaerobic, selenate-respiring bacterium, strain SES-3. Appl Environ Microbiol 60(8):3011–3019.

Oremland RS, Blum JS, Culbertson CW, Visscher PT, Miller LG, Dowdle P, Strohmaier FE (1994) Isolation, growth, and metabolism of an obligately anaerobic, selenate-respiring bacterium, strain SES-3. Appl Environ Microbiol 60(8):3011–3019

Pannico, A., El Nakhel, C., Kyriacou, M.C., Giordano, M., Stazi, S.R., De Pascale, S., Rouphael, Y., 2019. Combating micronutrient deficiency and enhancing food functional quality through selenium fortification of select lettuce genotypes grown in a closed soilless system. Front. Plant Sci. 10, 1495.

Patel PJ, Trivedi GR, Shah RK, Saraf M (2018) Selenorhizobacteria: as biofortification tool in sustainable agriculture. Biocatal Agric Biotechnol 14:198–203

Patel, et al., 1970. Selenium status of soils and common fodders in gujarat. Indian J. Agric. Sci. 40, 389–399.

Patharajan S, Raaman N (2012) Influence of arbuscular mycorrhizal fungi on growth and selenium uptake by garlic plants. Arch Phytopathol Plant Protect 45(2):138–151

Puccinelli, M., Malorgio, F., Pezzarossa, B., 2017. Selenium enrichment of horticultural crops. Molecules 22 (6), 933. https://doi.org/10.3390/molecules22060933.

Ramos, et al., 2010. Selenium biofortification and antioxidant activity in lettuce plants fed with selenate and selenite. Plant Soil Environ. 56 (12), 584–588.

Rana A, Joshi M, Prasanna R, Shivay YS, Nain L (2012) Biofortification of wheat through inoculation of plant growth promoting rhizobacteria and cyanobacteria. Eur J Soil Biol 50:118–126

Razaghi, A.; Poorebrahim, M.; Sarhan, D.; Björnstedt, M. Selenium stimulates the antitumour immunity: Insights to future research. Eur. J. Cancer **2021**, 155, 256–267.

Sanmartín P, DeAraujo A, Vasanthakumar A (2018) Melding the old with the new: trends in methods used to identify, monitor, and control microorganisms on cultural heritage materials. Microbial Ecol 76(1):64–80

Schilling K, Basu A, Wanner C, Sanford RA, Pallud C, Johnson TM, Mason PR (2020) Mass-dependent selenium isotopic fractionation during microbial reduction of seleno-oxyanions by phylogenetically diverse bacteria. Geochim Cosmochim Acta 276:274–288.

Schroder I, Rech S, Krafft T, Macy JM (1997) Purification and characterization of the selenate reductase from *Thauera selenatis*. J Biol Chem 272(38):23765–23768.

Sieprawska, et al., 2015. Involvement of selenium in protective mechanisms of Plants under environmental stress conditions – review. Acta Biol. Crac. Ser. Bot. 57 (1), 9–20.

Stoffaneller, R., Morse, N.L., 2015. A review of dietary selenium intake and selenium status in Europe and the Middle East. Nutrients 7, 1494–1537.

Sura-de Jong M, Reynolds RJ, Richterova K, Musilova L, Staicu LC, Chocholata I, Cappa JJ, Taghavi S, van der Lelie D, Frantik T, Dolinova I (2015) Selenium hyperaccumulators harbor a diverse endophytic bacterial community characterized by high selenium resistance and plant growth promoting properties. Front Plant Sci 6:p113.

Tamaoki, M., Freeman, J.L., Marques, L., Pilon-Smits, E.A.H., 2008. New insights into the roles of ethylene and jasmonic acid in the acquisition of selenium resistance in plants. Plant Signal. Behav. 3, 865–867.

Terry, et al., 2000. Selenium in higher plants. Annu. Rev. Plant Physiol. Plant Mol. Biol. 51, 401–432.

Tong, et al., 2014. Characterization of a selenium-tolerant rhizosphere strain from a novel Se hyperaccumulating plant Cardamine hupingshanesis. Sci. World J. 1–8.

Trivedi G, Patel P, Saraf M (2020) Synergistic effect of endophyti selenobacteria on biofortification and growth of *Glycine max* under drought stress. S Afr J Bot 134:27–35 ul Abadin Z, Yasin M, Faisal M (2017) Bacterial-mediated selenium biofortification of Triticum aestivum: Strategy for improvement in selenium phytoremediation and biofortification. Agriculturally important microbes for sustainable agriculture. Springer, Singapore, pp 299–315

Van Hoewyk, D., Takahashi, H., Inoue, E., Hess, A., Tamaoki, M., Pilon-Smits, E.A.H., 2008. Transcriptome analyses give insights into selenium-stress responses and seleniumtolerance mechanisms in Arabidopsis. Physiol. Plant. 132, 236–253

Wang P, Wang H, Liu Q, Tian X, Shi Y, Zhang X (2017) QTL mapping of selenium content using a RIL population in wheat. PLoS ONE 12(9):e0184351

Wang, M., Dinh, Q.T., Qi, M., Wang, M., Yang, W., Zhou, F., Liang, D., 2020. Radicular and foliar uptake, and xylem- and phloem-mediated transport of selenium in maize (*Zea mays* L.): a comparison of five Se exogenous species. Plant Soil 446, 111–123.

Wang, Y., Shu, X., Hou, J., Lu, W., Zhao, W., Huang, S., Wu, L., 2018. Selenium nanoparticle synthesized by *Proteus mirabilis* YC801: an efficacious pathway for selenite biotransformation and detoxification. Int. J. Mol. Sci. 19, 3809.

White, P.J., 2016. Selenium accumulation by plants. An. Bot. 117, 217–235.

Winkel, et al., 2015. Selenium cycling across soil – plant - atmosphere interfaces: a critical review. Nutrients 7, 4199–4239.

Winkel, L.H., Vriens, B., Jones, G.D., Schneider, L.S., Pilon-Smits, E., Banuelos, G.S., 2015. Selenium cycling across soil-plant-atmosphere interfaces: a critical review. Nutrients 7, 4199–4239.

World health statistics 2020: monitoring health for the SDGs, sustainable development goals. Geneva: World Health Organization; 2020. License: CC BY-NC-SA 3.0 IGO; https://creativecommons.org/licenses/by-nc-sa/3.0/igo. (access date: 16.01.2023).

Wu, Z., Banuelos, G.S., Lin, Z.-Q., Liu, Y., Yuan, L., Yin, X., Li, M., 2015. Biofortification and phytoremediation of selenium in China. Front. Plant Sci. 6, 136. https://doi.org/10.3389/fpls.2015.00136.

Xue, et al., 2001. Antioxidative and growth-promoting effect of selenium on senescing lettuce. Plant Soil 237 (1), 55–61.

Yao, X.; Chu, J.;Wang, G. Effects of selenium on wheat seedlings under drought stress. Biol. Trace Elem. Res. **2009**, 130, 283–290.

Yasin M, El-Mehdawi AF, Anwar A, Pilon-Smits EA, Faisal M (2015) Microbial-enhanced selenium and iron biofortification of wheat (*Triticum aestivum* L.)-applications in phytoremediation and biofortification. Int J Phytorem 17(4):341–347

Yasin, et al., 2015. Microbial-enhanced Selenium and Iron Biofortification of Wheat (Triticum aestivum L.) - Applications in Phytoremediation and Biofortification. Int. J. Phytoremediat. 17 (4), 341–347.

Ye Y, Qu J, Pu Y, Rao S, Xu F, Wu C (2020) Selenium biofortification of crop food by beneficial microorganisms. J Fungi 6(2):59

Yuan, L., Yin, X., Zhu, Y., Li, F., Huang, Y., Liu, Y., Lin, Z., 2012. Selenium in plants and soils, and selenosis in Enshi, China: implications for selenium biofortification. In: Yin, X., Yuan, L. (Eds.), Phytoremediation and Biofortification: Two Sides of One Coin. Springer Briefs in Molecular Science. Springer, Dordrecht, pp. 7–31.

Zahedi, S.M., Hosseini, M.S., Meybodi, N.D.H., Texeira da Silva, J.A., 2019b. Foliar application of selenium and nano-selenium affects pomegranate (*Punica granatum* cv. Malase Saveh) fruit yield and quality. S. Afr. J. Bot. 124, 350–358.

Zanetti, M., Correa, L., Netto, A.S., Cunha, J., Santana, R., Cozzolino, S., 2015. Influence of canola oil, vitamin E and selenium on cattle meat quality and its effects on nutrition and health of humans. In: Banuelos, G.S., Lin, Z.-Q., Moraes, M.F., Guilherme, L.R.G., dos Reis, A.R. (Eds.), Global Advances in Selenium Research from Theory to Application: Proceedings of the 4th International Conference on Selenium in the Environment and Human Health. CRS Press, London, UK, pp. 97–98.

Zhang, J.; Taylor, E.W.; Bennett, K.; Saad, R.; Rayman, M.P. Association between regional selenium status and reported outcome of COVID-19 cases in China. Am. J. Clin. Nutr. **2020**, 111, 1297–1299.

Zhao, et al., 2005. Study on the relationship between soil se and plant se uptake. Plant Soil 277 (1), 197–206.