

Review

Biofortification with Selenium: Implications for the Resilience and Nutritional Value of Plants Under Changing Climate Conditions

Kevin Böhm ¹ , Shahrzad Safinazlou ^{1,2,3} , Jean-Philippe Reichheld ^{2,3} , Muhammad Jawad Nasim ^{1,*}  and Claus Jacob ^{1,*} 

- ¹ Division of Bioorganic Chemistry, School of Pharmacy, Saarland University, 66123 Saarbruecken, Germany; kevin.boehm@uni-saarland.de (K.B.); shahrzad.safinazlou@gmail.com (S.S.)
² Laboratoire Génome et Développement des Plantes, Université Perpignan Via Domitia, F-66860 Perpignan, France; jean-philippe.reichheld@univ-perp.fr
³ Laboratoire Génome et Développement des Plantes, CNRS, F-66860 Perpignan, France
* Correspondence: jawad.nasim@uni-saarland.de (M.J.N.); c.jacob@mx.uni-saarland.de (C.J.); Tel.: +49-681-302-57335 (M.J.N.); +49-681-302-3129 (C.J.)

Abstract

Selenium (Se) is an essential trace element in animals and humans, usually acquired via nutrition and thus often dependent on the Se content of the soil from where the food crops originate. The uneven distribution of Se in soils may therefore result in regional Se deficiencies, often further exacerbated due to climate change and its subsequent effects on Se speciation (i.e., the chemical forms in which Se occurs) and the element's mobility. In recent years, biofortification has emerged as a promising approach to address this issue. This review provides an overview of how climate-driven changes in Se cycling influence soil Se availability and discusses the resulting implications for plant resilience, crop biofortification and dietary Se supply. Although plants do not require Se per se, an increased Se content of plants may improve their yields, antioxidant defences, and tolerance to various—climate (change)-related—stresses such as drought, salinity, and oxidative stress at low concentrations. So far, selenite (SeO_3^{2-}) and selenate (SeO_4^{2-}) are the most commonly employed Se species in agriculture, often via foliar and soil applications, and due to their excellent solubility in water are subject to leaching or other weather-related limitations. Alternative Se compounds, such as Se nanoparticles (SeNPs) and selenium sulfide (SeS_2) present promising approaches that may enable a more controlled Se release in soils. Nonetheless, their long-term agronomic performance and environmental behaviour require further investigations.

Keywords: biofortification; climate change; food chain transfer; selenium deficiency; soil selenium



Received: 3 June 2026

Revised: 20 July 2026

Accepted: 29 July 2026

Published: 6 August 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Modern human activities have triggered a rapid climate change at a rate that has been unprecedented during the last 2000 years, each of the last decades becoming successively warmer than the decade before [1]. Besides causing frequent disasters such as storms and wildfires, temperature rises and subsequent changes in climate conditions have also influenced the available soil content of macro- and micronutrients such as selenium (Se). Selenium exists in soil in inorganic (Se^{2-} , Se^0 , SeO_3^{2-} , SeO_4^{2-}) and organic forms including

methyl selenides, trimethylselenonium ions, and selenium-containing amino acids [2,3]. Heavy rainfall, for instance, tends to decrease Se concentrations in soils by intensifying the leaching of soluble forms, while prolonged dryness (high aridity index) creates oxidizing conditions which favour the formation of mobile oxyanions such as selenite (SeO_3^{2-}) and selenate (SeO_4^{2-}) [4]. These oxyanions are readily washed out during subsequent wet periods. Global modelling studies suggest that under moderate climate scenarios, roughly two-thirds of the world's croplands could lose a mean of 8.7% of their Se content by the end of the century [5]. The most severe reductions in Se content in soil are expected in intensively farmed regions characterized by high soil pH and low clay content. Changing soil moisture, rising aridity, and warming-induced increases in soil respiration may further accelerate volatilization and the release of Se. Although the model did not distinguish between individual crop species, declining soil Se concentrations may ultimately reduce Se levels in food crops and thereby affect plant resilience as well as the nutrition of animals and humans consuming these plants [4–6].

Notably, several regions worldwide, including temperate humid to sub-humid regions of China as well as large areas of Europe, the United States, and Canada, already suffer from Se deficiency. In British Columbia, Canada, for instance, low Se concentrations have been reported in corn silage, barley, oats, grasses, legumes and, less frequently, wheat [7–9]. To deal with Se deficiency in crop plants, most strategies to date have relied on fortification approaches through soil, in hydroponic cultures or through foliar application with soluble oxyanions, such as SeO_3^{2-} and SeO_4^{2-} , although the efficiency of these methods remains questionable due to leaching and other soil processes that reduce long-term availability [10–13].

Interestingly, Se fortification of soil does not solely benefit populations with Se deficiency. Although most plants are not considered strictly dependent on Se for survival, low concentrations of Se can bring significant benefits to them as Se influences fundamental physiological processes in many plants, including improving water status, respiratory efficiency, and photosynthetic performance [14,15]. In addition to higher crop yields and performance, Se also strengthens antioxidant defence systems, enabling plants to better withstand oxidative damage—and such an enhanced redox capacity even translates into increased tolerance against a wide spectrum of stresses, including drought, salinity, intense light, and heavy metal exposure [15,16].

In humans, as well as in livestock, Se takes on diverse biological functions, most notably in antioxidant defence, thyroid hormone production and activation, cancer prevention, immune system regulation, glucose metabolism, and modulation of gut microbiota [5,17,18]. Its deficiency is closely linked to an impaired immune function and an increased susceptibility to infections, and, in the case of a prolonged insufficiency, disorders such as Kashin–Beck disease and Keshan disease, as well as an increased risk of AIDS, cancer, cardiovascular disease, inflammatory bowel disease, infertility and reproductive problems [19,20]. It is estimated that between 500 million and 1 billion people worldwide have insufficient intakes of Se, underlining the importance of Se in soil and its influence on human health [21]. While selenium deficiency in humans and livestock can be remedied through supplementation, for instance via selenium-rich yeast, Na_2SeO_3 or Na_2SeO_4 added to table salt, or selenocysteine (SeCys)- and selenomethionine (SeMet)-containing multivitamin–multimineral preparations, agronomic biofortification of crops offers the additional advantage of simultaneously enhancing plant resilience and growth [22–24]. Furthermore, biofortification of crops, in contrast to human supplementation regimes, also makes it easier to address Se deficiency in older, rural and low-income populations, since it does not require compliance and eventually is also more cost effective [23].

Rather than focusing solely on Se fortification strategies, this review therefore aims to address the impact of climate change on the Se cycle and to highlight the resulting consequences for plant resilience, crop fortification, and dietary Se supply. By integrating environmental, agricultural, and nutritional perspectives, this review is an attempt to provide a broader overview for understanding the role of Se biofortification under changing climatic conditions. The agronomic efficiency and environmental limitations of different fortification approaches are compared, and selenium sulfide (SeS₂) is discussed as a promising, yet still largely unexplored, alternative strategy that may enable more effective and sustained release of both Se and S over time.

2. The Impact of Climate Change on Se Deficiency in Soil and Se Bioavailability

The geological source of Se is the primary factor determining its status in the surface soil, although atmospheric deposition these days also plays a role, contributing up to 85% of the annual selenium influx in top soil—corresponding to 0.04–0.23 mg Se m^{−2} Per year [25,26]. The majority of the rock-types around the world consists of low-Se rocks (0.05–0.09 mg Se kg^{−1}), subsequently also accounting for a low Se content of most soils [27]. Apart from a few regions with exceptionally high Se contents in soil, such as in the Midwestern states of the USA and around Limerick in Ireland, very low to low Se contents, corresponding to the concentrations of ≤0.125 mg kg^{−1} and 0.125–0.175 mg kg^{−1}, respectively, are found across expansive domains of the United States, eastern South America, Europe, Africa, eastern Asia, and Australia [28,29].

In the future, this already low level of Se in most soils may even decrease further due to climate change. According to the report of Intergovernmental Panel on Climate Change (IPCC) in 2021, an average global increase of 1.5 °C in temperature is predicted until 2040, which can culminate in decreased Se levels in soils by speeding volatilization and changing Se speciation and/or mobility [30]. Not surprisingly, the influence of temperature on the Se content of soil has been investigated for many years. In 1990, Calderone et al. reported that increasing the incubation temperature of sediment samples from 15 °C to 35 °C for 20 weeks enhanced Se volatilization by stimulating microbial activity in alkaline soil rich in organic matter. This process involves the microbial conversion of inorganic Se into volatile alkyl selenides, including dimethyl selenide [31]. Similarly, repeated freeze–thaw cycles in regions such as Antarctica increase available organic material and consequently also the microbial activity which can induce one- to four-fold increases in the rate of Se volatilization [32].

Importantly, climate change is not limited to higher temperatures alone; it can also intensify the global water cycle, i.e., causing intense rainfall and associated flooding in humid regions, such as South and Southeast Asia and intense drought periods in many subtropical, semi-arid and already dry regions, such as the Mediterranean Basin and Sub-Saharan Africa. Evapotranspiration—the loss of water from land to atmosphere via evaporation from soil and transpiration from plant tissues—as well as decreased precipitation patterns are two major drivers causing exacerbated droughts in such areas [30,33]. Under changing climatic conditions, both prolonged droughts and heavy rainfalls can increase the mobilization and subsequent loss of Se from soils. The argument that droughts mobilize Se may seem counterintuitive at first, yet this is due to the special chemistry of Se and its quite soluble oxyanions [34]. Additionally, during periods of drought, evapotranspiration leads to increased uptake of Se by plants, where it is subsequently volatilized. Therefore, the aridity index, calculated as the ratio of potential evapotranspiration to precipitation, strongly influences Se concentrations in soils. An increased aridity index is associated with dryness and aeration of the soils, leading to the oxidation of Se species and the formation of

oxyanions, such as SeO_3^{2-} and SeO_4^{2-} [5]. These more-oxidized oxyanions have a higher solubility and mobility in soil, resulting in leaching in the subsequent precipitation events and loss of Se, especially during high precipitation periods [35].

Consistent with these relationships, selenium-deficient soils in northeastern Brazil are predominantly associated with semi-arid regions, highlighting climate and pedogenesis as decisive factors for the availability of Se in the soil [36]. Similarly, precipitation gradients in Hawaii demonstrate that the amount of precipitation significantly influences Se speciation and mobility, with both arid conditions and excessive rainfall favouring Se remobilization as well as losses via leaching [37].

As for the extent of Se loss in soil due to climate change, the predictive model introduced by Jones et al., which is based on the analysis of 33,241 global soil samples, suggests that the global mean of soil Se for the period of 1980–1999, namely 0.322 mg kg^{-1} (close to the reported global value of 0.4 mg kg^{-1}), is going to decline by 8.4% on average in 2080–2099 under moderate climate change, with 66% of croplands losing 8.7% Se [5]. Other machine learning models, such as Lin-SVR and MLP, have been used to predict changes more precisely on a smaller scale for regions such as Europe, with gradients of climate, soil organic carbon and atmospheric Se deposition as prediction factors. Based on these models, Se concentrations in Scandinavian soils are projected to increase by up to approximately 5%, partly driven by evapotranspiration, whereas Mediterranean soils may experience decreases of a similar magnitude due to increasing aridity and associated Se losses by 2100 [4].

As briefly mentioned at the beginning of the section, another important factor governing the concentration of Se in soil is the atmospheric level of Se which is deposited onto the Earth's surface by precipitation. A study by Feinberg et al. employed a global aerosol–chemistry–climate model to estimate Se deposition from 2005 to 2009, and to project future deposition patterns for 2095–2099 [26]. For the period between 2005 and 2009 the model predicted hotspots with up to $>1 \text{ mg m}^{-2}$ per year of Se deposition over large oceanic areas as a result of volatile marine biogenic emissions, as well as over East Asia, eastern Europe, and the eastern US, i.e., regions associated with high anthropogenic Se emissions originating from, for instance, fossil fuel combustion and industrial processes [26]. Notably, these regions largely overlap with areas historically affected by elevated S deposition and acid rain, reflecting the common influence of industrial and energy-related atmospheric emissions [38,39]. Based on the model proposed by Feinberg et al., Se deposition approximately doubled between the 1980s and 2000s in China and India, which aligns with the economic upturn and the resulting increase in coal combustion in these areas [26,40]. Indeed, experimental findings on the soil of Hainan Island, a city with higher Se content compared to the baseline value of Chinese soil, are in agreement with the results of the predictive model and even introduce wet depositing and precipitation as a critical source for high Se content in this region [41]. Although the majority of Se in the soil ultimately originates from geological parent material as a long-term source, Yu et al. and Song et al. highlighted that atmospheric deposition constitutes a significant current source of Se input into the topsoil in parts of China, and thus can significantly influence present-day Se availability [25,42]. In contrast, dry areas such as eastern ocean basins and the Sahara are rather low in Se deposition.

So where does this Se in the atmosphere originate from? As mentioned before, soil and marine microorganisms are able to generate volatile organic Se compounds (VOSeC), and, more recently, burning fossil fuels has become another major source of volatile Se in the atmosphere (Figure 1). Yet since the 1980s, the overall anthropogenic emissions of sulfur have decreased in North America and Europe as a consequence of moving away from coal energy towards renewable sources. Due to the chemical similarities between S and

Se, particularly their co-emission in high-temperature combustion processes, Se emissions have also decreased in parallel during this period. Consequently, the global Se deposition is projected to decrease further by the end of the twenty-first century compared to the 2005–2009 period [26].

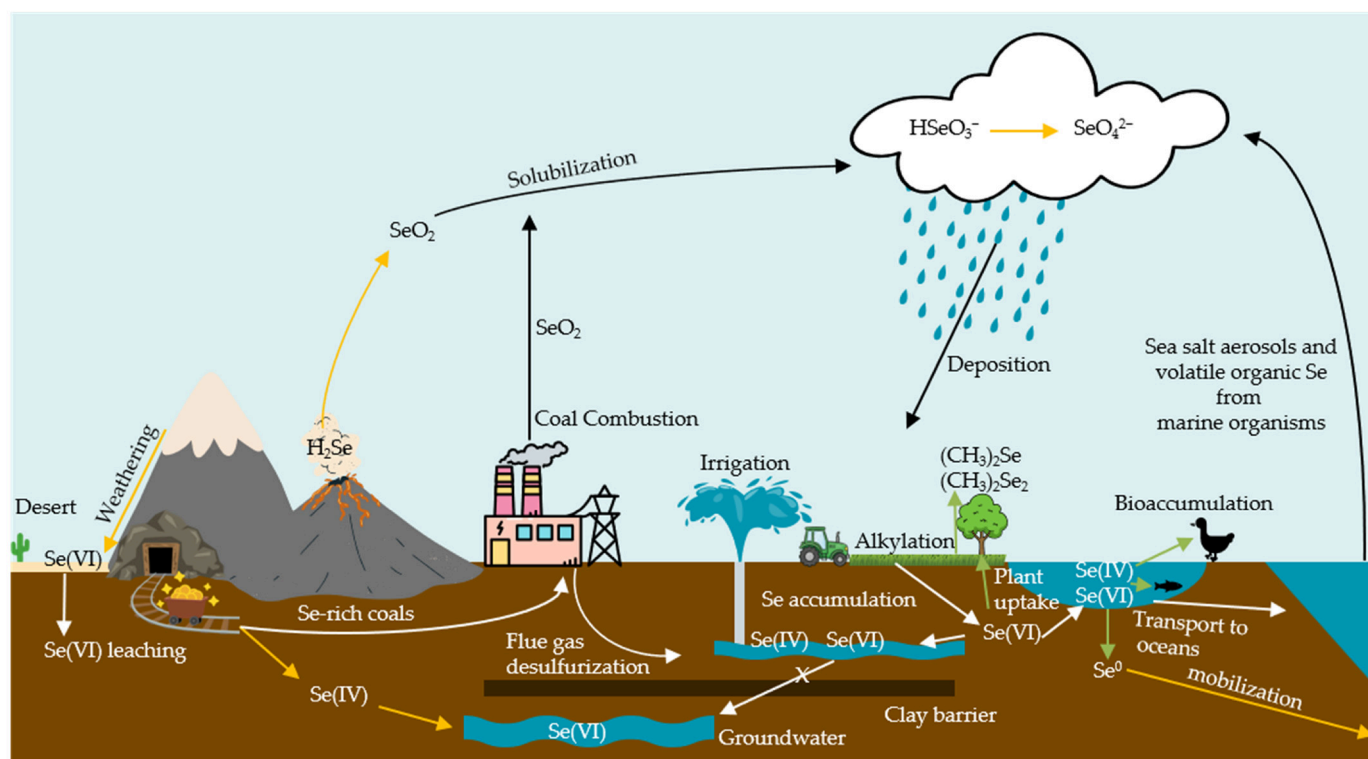


Figure 1. A conceptual model for global Se cycling. Adapted from Reynolds and Pilon-Smiths and generated using Canva and PowerPoint [43]. The arrows in orange indicate processes that involve oxidation, while the green arrows indicate reduction. Se enters the atmosphere mainly as SeO_2 from coal combustion and volcanic activity. In the atmosphere, it dissolves in moisture and is oxidized to selenate, which is deposited into soils via precipitation. In soils and groundwater, Se can be reduced again to selenite and subsequently re-enter the surface environment through irrigation or uptake by plants, the latter converting inorganic Se into organic Se compounds. Se can further be transported into rivers, lakes, and oceans, where it becomes accumulated and volatilized by aquatic organisms. Additional selenium sources in soils include mining activities and the weathering of rocks.

Notably, there may be some exceptions, such as areas over the eastern Pacific and Southern Ocean, that are predicted to experience a rise in Se deposition caused by changes in precipitation and heightened marine biogenic emissions due to the decline of sea ice. As the deposition to agricultural soils in the Southern Hemisphere is less influenced by anthropogenic emissions, Se deposition over Africa, Australia, and South America is likely to decrease modestly in the future, ranging in decreases from 3 to 25% while deposition on agricultural soil in Asia, North America, and Europe is expected to decrease sharply at the end of the twenty-first century [26]. Although a decrease in anthropogenic liberation of Se—and especially S—into the atmosphere, for instance by burning fewer fossil fuels, may initially be seen as a positive development, from the perspective of Se in soil, reduced atmospheric deposition, in combination with the future predicted effects of climate change on the Se concentration of soil, is perhaps less welcome, as it may imply a depletion of Se contents of soils worldwide.

While climate-induced changes play a major role in Se volatilization and speciation, environmental stresses also directly affect the acquisition of Se by plants. Drought, for

instance, can substantially reduce the Se uptake by plants due to reduced soil moisture which hinders the diffusion and mass flow of Se species toward the roots. Conversely, increased soil aeration under drought conditions leads to the oxidation of reduced Se species into the more mobile oxyanions SeO_3^{2-} and SeO_4^{2-} which are more bioavailable [35,44].

In contrast to drought, increased soil moisture resulting from heavy rainfall and flooding promotes reducing conditions in the soil. Consequently, bioavailable Se species may be reduced to less bioavailable forms—namely, elemental Se or selenide (Se^{2-}) [3,37,44].

In summary, environmental conditions do not uniformly decrease or increase Se uptake, rather, they alter Se speciation, mobility and bioavailability, which leads to context-dependent responses [37,44].

3. Biofortification of Crops Through Soil Application of Se Species

Although Se is not considered an essential element for most plants, biofortification with this element still provides three very important benefits. Low to moderate Se supplementation has repeatedly been shown to improve plant growth, yield, and the quality of crops [10,23,45,46]. Additionally, Se enhances antioxidant capacities and plant stress tolerance by inducing the synthesis of not only selenium-bearing amino acids such as selenocysteine (SeCys) and selenomethionine (SeMet), yet also several secondary metabolites involved in stress defence, such as phenolic compounds, flavonoids, glucosinolates, terpenes, and alkaloids [17,47,48]. The origin of these positive effects is attributed to the Se-mediated enhancement of antioxidant defences through the accumulation of these bioactive compounds together with improvements of photosynthesis and ion homeostasis. By limiting the accumulation of reactive oxygen species, maintaining membrane integrity, and supporting metabolic activity under adverse conditions, Se can enhance the ability of plants to tolerate drought, salinity, and other abiotic stress factors [15,49]. Furthermore, several studies have demonstrated that agronomic biofortification can significantly increase Se concentrations in edible plant parts without decreasing the yield (Table 1) [12,13,45,46,50–63]. Therefore, agronomic biofortification—i.e., the enrichment of crops with essential micronutrients through agricultural practices such as fertilization—represents one of the most effective and sustainable strategies for combating Se deficiency in agriculture [64].

Especially the foliar application of SeO_4^{2-} has been proven to be highly effective in crops such as wheat, maize, and soybean due to its higher bioavailability and mobility compared to SeO_3^{2-} [45,51–53]. In soybean, foliar fertilization with SeO_4^{2-} (100 g Se ha^{-1}) increased the Se concentration in seeds from 0.09 mg kg^{-1} to 16 mg kg^{-1} , with approximately 95% of the accumulated Se converted into organic forms. Similarly, foliar application of SeO_4^{2-} in maize at 100 g Se ha^{-1} increased grain Se concentrations from 27 to 523 $\mu\text{g kg}^{-1}$, corresponding to an approximately 19-fold increase [52]. Moving from cereals to vegetables, one finds lettuce and tomatoes to be good accumulators of Se. Hydroponic lettuce has been shown to exhibit a strong capacity for Se biofortification, efficiently converting the SeO_4^{2-} and SeO_3^{2-} applied into organic Se (predominantly selenomethionine)—and enhanced photosynthesis and growth of lettuce have been observed at optimal Se concentrations of 2–4 $\mu\text{mol L}^{-1}$ [55]. Studies on hydroponically grown tomatoes have also demonstrated that sodium selenite biofortification increases Se concentrations in the fruit, antioxidant capacity, and nutraceutical quality, with optimal responses generally observed at moderate Se application rates (11.56 $\mu\text{mol L}^{-1}$) [10,50,57]. At the same time, experiments with lettuce demonstrated that selenite is often safer and more effective in promoting plant growth, whereas selenate is translocated better into the edible parts of the plants [49,55].

Among the two dominant species used for biofortification, namely SeO_3^{2-} and SeO_4^{2-} , the latter is generally more mobile in soil, whereas SeO_3^{2-} tends to bind more strongly to soil particles and therefore is more readily incorporated into organic Se forms within

plants [13]. Soil enrichment with 5–10 mg kg^{−1} SeO₄^{2−} in lettuce grown on calcareous soil, for instance, produced ten-fold greater Se levels in the shoots compared to the equivalent SeO₃^{2−} treatments [13]. Then again, SeO₃^{2−} tends to promote the formation of organic Se species—such as SeCys and SeMet—as demonstrated in wheat following the soil application of 2 mg kg^{−1} Na₂SeO₃ [45].

Table 1. Representative examples of Se biofortification in major crop species and their reported physiological or nutritional benefits.

Crop Species	Se Source	Application Method	Reported Effect	Ref.
<i>Triticum aestivum</i> L. (wheat)	Na ₂ SeO ₃ /Na ₂ SeO ₄	Soil and foliar	Increased grain Se concentration and bio-accessibility	[45]
<i>Glycine max</i> (L.) Merr. (soybean)	Na ₂ SeO ₄	Foliar	Increase from 0.09–16 mg kg ^{−1} seed Se; ~95% organic Se	[51,63]
<i>Zea mays</i> L. (maize)	Na ₂ SeO ₄	Foliar	Increased grain Se concentration	[52,53]
<i>Lactuca sativa</i> L. (lettuce)	Na ₂ SeO ₃ /Na ₂ SeO ₄	Hydroponic and soil	Enhanced Se accumulation, photosynthesis and growth	[10,12,13,55]
<i>Oryza sativa</i> L. (rice)	SeNPs	Seed soaking/Foliar	Improved salinity tolerance and growth	[11]
<i>Brassica oleracea</i> var. <i>italica</i> Plenck (broccoli)	Na ₂ SeO ₄	Soil/Foliar	Enhanced Se content and glucosinolate	[59–61]
<i>Camellia sinensis</i> (L.) Kuntze (tea)	Various Se fertilizers	Soil/Foliar	Increased Se accumulation and quality traits	[58,62]

Overall, such studies indicate a trend in which SeO₄^{2−}—compared to other Se species—exhibits inherently greater mobility regarding translocation into edible tissues [12,47,60]. This makes it especially suitable for biofortification purposes. SeO₃^{2−}, on the other hand, is more frequently incorporated into organic Se compounds and may thus exert stronger growth-promoting effects when applied in moderate amounts [12,45,55]. Furthermore, the positive effects of Se fortification on plant growth, antioxidant capacity, and stress tolerance have been demonstrated across various species, including cereals, vegetables, and horticultural crops [15,45,50,51]. This suggests that plant responses to Se are shared across different plant groups. Despite possible differences in magnitude of the response, it stems from broader physiological effects associated with Se metabolism in plants [15,49].

Beyond Se accumulation in plants, Se supplementation also provides several benefits to plants; for instance it has been widely shown to mitigate abiotic stress [11,49,65–68]. Drought stress limits wheat productivity significantly, and fertigation and foliar Se applications can maintain the water status and improve yields under water-deficit conditions [66]. Foliar or seed-soaking treatments with selenium nanoparticles (SeNPs), which are considered less toxic and potentially more bioavailable than inorganic Se species, at 6.25 mg L^{−1} may even enhance salinity tolerance in rice by improving root architecture, photosynthetic efficiency, and growth parameters [69]. Nevertheless, the reported benefits vary considerably among species and stress conditions, and optimal selenium forms and dosages so far remain insufficiently defined for many crop systems.

Despite these promising findings, several limitations remain. The positive effects of Se are highly dose-dependent, and the margin between beneficial and potentially toxic

concentrations is relatively narrow. In addition, the range between beneficial and optimal application rates can differ substantially among crop species, requiring careful optimization of Se fertilization strategies to maximize agronomic benefits while minimizing phytotoxicity and avoiding excessive Se accumulation [2,44,64]. Furthermore, although the application of Se on soil is simple and scalable, it is also prone to leaching and volatilization, particularly for SeO_4^{2-} under heavy rainfall or irrigation, which are predicted to intensify with climate change [70]. Foliar application allows a more precise Se delivery and rapid tissue absorption, yet its effectiveness also depends on the weather, since rainfall can wash away soluble Se salts from leaves, requiring multiple applications [71]. Moreover, uneven spray coverage may cause heterogeneity in Se accumulation across plant tissues, although this may be circumvented in the future by applying specifically designed intelligent spray-robots and drones [72,73].

To overcome these limitations with the technologies available already, less soluble depot-like Se substances may be considered, such as nanostructured and organic Se fertilizers, which have been investigated as possible alternatives [44,74,75]. SeNPs, for instance, exhibit reduced leaching and lower toxicity, leading to improved yields and enhanced antioxidant responses [76]. Simultaneously, organic selenium fertilizers—such as selenium-enriched green manure, selenium-containing peat, and plant-derived organic selenium compounds, including SeMet and SeCys—have garnered increasing attention due to their gradual selenium release and their ability to promote the accumulation of bioavailable organic selenium species in edible plant tissues [77–79]. A further promising yet un(der)explored candidate is selenium sulfide SeS_2 , a group of compounds of the general formula $\text{Se}_x\text{S}_{8-x}$ in essence chemically resembling a mixture of Se and S at the molecular level [80]. Although insoluble in water, selenium sulfide may gradually degrade in soil, potentially releasing SeO_3^{2-} and SO_4^{2-} at a controlled rate, thus minimizing Se leaching and toxicity while simultaneously supplying both nutrients (S and Se) for plant defence metabolism [81,82]. Its dual nutrient content and gradual degradation suggest a potentially attractive approach for sustainable biofortification, although experimental evidence regarding its agricultural uses remains limited. It is actually interesting that both elemental Se and SeS_2 under oxidative conditions degrade more rapidly and thus become more (bio-)available. They may potentially act as “smart” depots which become activated under arid and oxidative conditions, i.e., at times when plants need them most, although this concept still requires experimental validation under realistic agricultural conditions [83]. Eventually, such Se depots could be rather useful in biofortification and should be studied in more detail.

4. Se Biofortification and Transfer Along the Food Chain

The correlation between Se in soil, plants, food and human serum has been studied extensively over the years and highlights the transfer of Se along the entire food chain—from the soil, through plants and animals, to humans [83–85]. In this process, Se is absorbed by plants—primarily in the form of selenite or selenate—and converted into organic compounds such as SeCys and SeMet. Through plants, these compounds enter the human diet either directly via plant-based foods or indirectly through the consumption of animal products, such as milk, eggs, or meat (Figure 2) [83–85]. Consequently, low soil Se availability is frequently associated with reduced Se concentrations in crops, forage, livestock, and ultimately human serum [84].

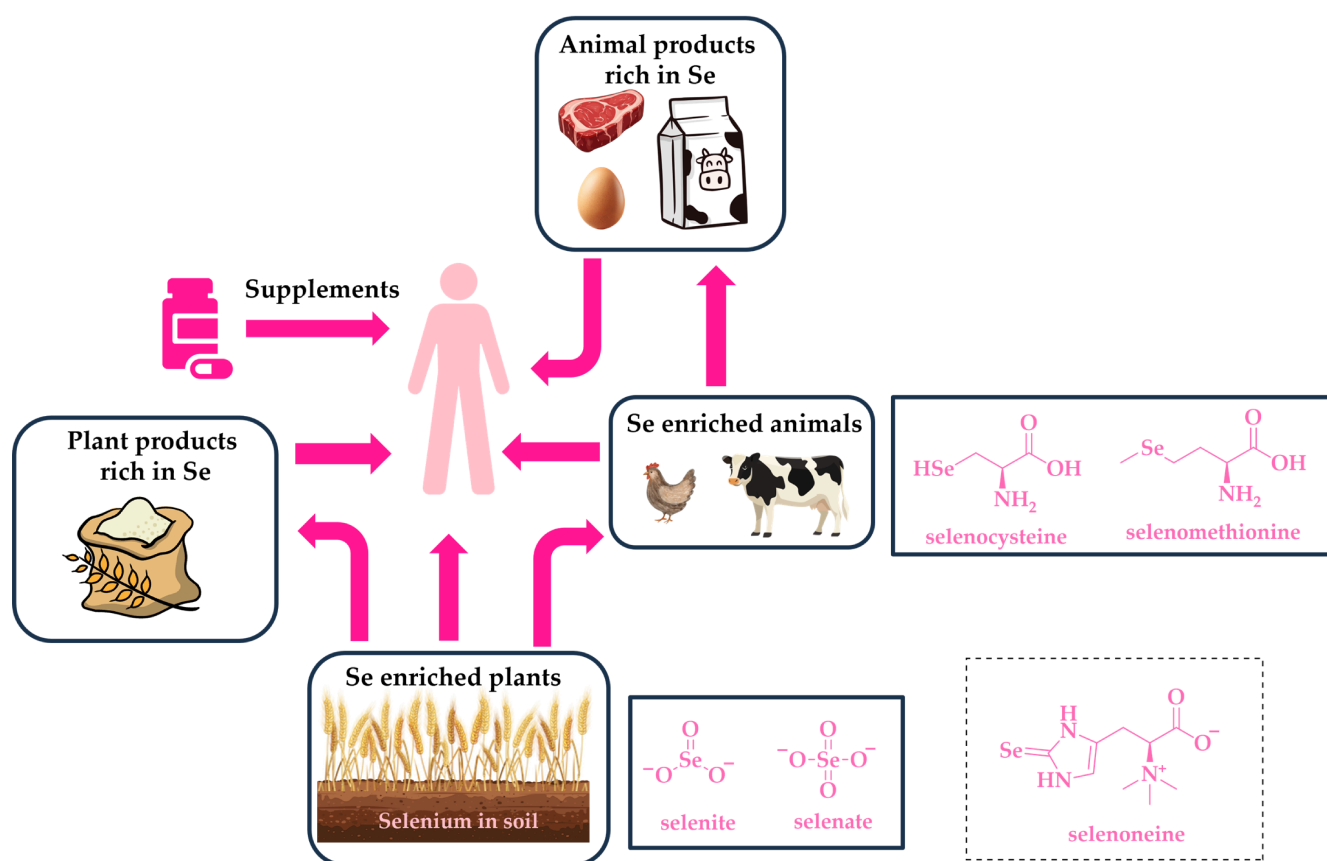


Figure 2. Simplified food chain depicting human Se intake from Se-enriched plant and animal sources as well as supplementation. The chemical structures of selenite, selenate, SeCys and SeMet as well as selenoneine (found in aquatic and marine animals) are also presented.

The biofortification of plants via fertilizing soils with soluble or depot-like forms of Se therefore may not only benefit the plants and counteract some of the stresses caused by climate change. It also impacts the consumers of such plants, i.e., animals and humans. Comparing soil Se concentrations with human serum Se levels suggests that Se deficiency in many populations is largely driven by the low Se content of local soils, a pattern that is often evident in Central and eastern Europe and parts of East Asia, especially China. [86,87]. Additional regions with low soil and low serum Se levels are found in Western and Southeastern Africa [88–98].

A well-documented example illustrating the interconnectedness across the entire food chain is Finland, where Se-containing fertilizers have been employed since 1985 to counteract the population's Se deficiency [99]. As a result of this intervention, Se concentrations in crops, animal feed, livestock, and ultimately in human blood serum have each risen about two-fold, thereby demonstrating how targeted agronomic biofortification can influence Se levels throughout the entire food chain [99].

Nevertheless, human Se intake depends upon multiple factors, including soil geochemistry, Se speciation and bioavailability, climatic conditions, agricultural practices, dietary habits, socioeconomic factors, and the consumption of non-regional, imported foods or Se supplements [83,85,100]. In this context, the international food trade can decouple dietary Se intake from local soil conditions—especially in industrialized countries that rely on imported grain and animal feed [100]. Since the primary source of Se for humans is their diet, particularly cereals, meat, fish, and dairy products, an integration of soil geochemistry and dietary patterns with human biomonitoring data is essential for Se deficiency hotspots

to be identified and addressed through targeted biofortification or tailor-made dietary strategies [101].

5. Conclusions

Selenium is an essential trace element for animals and humans and, despite not being essential for plants, also benefits many of them by increasing yields and their resilience against abiotic stresses. Since the Se content in most soils is low, and climate change is going to further exacerbate the already existing Se imbalance by increasing its mobility and thus escape, boosting the Se content of soils by adding soluble or depot-like Se substances holds considerable promise for a number of reasons. It not only serves as a means of the biofortification of plants, especially under drought, oxidative and metal stress conditions. At the same time, it also increases the dietary Se supply for the consumers of these plants, be it either animals or humans. Among the various Se forms and application methods, soil and foliar applications of SeO_3^{2-} and SeO_4^{2-} are the most commonly employed approaches so far, although alternative and more sustainable methods and sources, such as SeS_2 , represent promising avenues for future research. Less soluble and biodegradable forms of Se, for instance, may serve as long-term Se depots, gradually degrading to release both Se and S into the soil. Still, these potential advantages remain largely hypothetical, and the agronomic performance, environmental behaviour and long-term effectiveness of such approaches under field conditions remain insufficiently explored.

Although significant progress has recently been made in research on Se biofortification, important knowledge gaps remain. Still, reliable implementation of selenium biofortification across diverse crops, soil types, and agricultural systems will require a better understanding of the bioavailability of selenium, crop-specific selenium requirements, long-term environmental effects, and the interactions between climate-driven changes in soil chemistry and selenium uptake. Future research should, therefore, focus on the impact of climate-driven changes in soil chemistry on Se bioavailability and plant uptake. In this context, crop-specific Se requirements must be determined, and application strategies optimized accordingly under realistic conditions. Furthermore, studies on the long-term effects of Se biofortification on the environment and microbiota are also needed, as this aspect is currently insufficiently explored and understood.

As the consequences and challenges of climate change, together with demographic changes in many populations and thus increased needs for healthy eating, especially in the elderly, are becoming ever more apparent and imminent, research into these various uses and benefits of Se supplementation in agriculture is therefore clearly necessary and may bestow the term “lunar gardening” with an entirely new meaning.

Author Contributions: Conceptualization, C.J., J.-P.R. and M.J.N.; methodology, K.B. and S.S.; writing—original draft preparation, C.J.; writing—review and editing, K.B., S.S. and M.J.N.; supervision, C.J. and J.-P.R.; project administration, K.B. and M.J.N. All authors have read and agreed to the published version of the manuscript.

Funding: Authors would like to acknowledge the financial support provided by the University of Saarland, Saarbruecken, Germany. The authors would also like to thank the Saarland University Internationalization Fund for supporting the project “Plant Fortification Project between Saarland and French Partners in Occitania (Saar-Occ)”. Authors would also like to acknowledge the Support provided by the LETSGROW project, funded by the European Union under the Horizon Europe Programme, Grant Agreement No. 101217477.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors would like to thank Sodomir Popojuk and Ken Rory for their advice, discussions, and proof-reading of the manuscript. Special thanks go to many other colleagues from the Academiae International network (www.academiae.eu) (accessed on 12 May 2026) and the “Pharmasophy” team for their helpful discussions and advice.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Allan, R.P.; Arias, P.A.; Berger, S.; Canadell, J.G.; Cassou, C.; Chen, D.; Cherchi, A.; Connors, S.L.; Coppola, E.; Cruz, F.A. Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2023; pp. 3–32.
2. Yang, H.; Yang, X.; Ning, Z.; Kwon, S.Y.; Li, M.-L.; Tack, F.M.G.; Kwon, E.E.; Rinklebe, J.; Yin, R. The Beneficial and Hazardous Effects of Selenium on the Health of the Soil-Plant-Human System: An Overview. *J. Hazard. Mater.* **2022**, *422*, 126876. [[CrossRef](#)] [[PubMed](#)]
3. Kabata-Pendias, A.; Pendias, H. *Trace Elements in Soils and Plants*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2001.
4. Jones, G.D.; Insinga, L.; Droz, B.; Feinberg, A.; Stenke, A.; Smith, J.; Smith, P.; Winkel, L.H.E. Emerging Investigator Series: Predicted Losses of Sulfur and Selenium in European Soils Using Machine Learning: A Call for Prudent Model Interrogation and Selection. *Environ. Sci. Processes Impacts* **2024**, *26*, 1503–1515. [[CrossRef](#)] [[PubMed](#)]
5. Jones, G.D.; Droz, B.; Greve, P.; Gottschalk, P.; Poffet, D.; McGrath, S.P.; Seneviratne, S.I.; Smith, P.; Winkel, L.H.E. Selenium Deficiency Risk Predicted to Increase under Future Climate Change. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 2848–2853. [[CrossRef](#)] [[PubMed](#)]
6. Pi, K.; Van Cappellen, P.; Li, H.; Gan, Y.; Tong, L.; Zhong, X.; Wang, Y. Soil Respiration Induces Co-Emission of Greenhouse Gases and Methylated Selenium from Cold-Region Mollisols: Significance for Selenium Deficiency. *Environ. Int.* **2024**, *188*, 108758. [[CrossRef](#)] [[PubMed](#)]
7. Liu, H.; Wang, X.; Zhang, B.; Han, Z.; Wang, W.; Chi, Q.; Zhou, J.; Nie, L.; Xu, S.; Liu, D. Concentration and Distribution of Selenium in Soils of Mainland China, and Implications for Human Health. *J. Geochem. Explor.* **2021**, *220*, 106654. [[CrossRef](#)]
8. National Research Council (US) Subcommittee on Selenium. *Selenium in Nutrition: Revised Edition*; National Academies Press: Cambridge, MA, USA, 1983.
9. Miltimore, J.E.; Ryswyk, A.L.V.; Chapman, F.M.; Kalnin, C.M.; Pringle, W.L. Selenium Concentrations in British Columbia Forages, Grains, and Processed Feeds. *Can. J. Anim. Sci.* **1975**, *55*, 101–111. [[CrossRef](#)]
10. Huang, S.; Ying, Z.; Chen, J.; Yang, Y.; Zhang, J.; Yang, L.; Liu, M. Effect of Selenium Application on Growth, Antioxidative Capacity, and Nutritional Quality in Purple Lettuce Seedlings. *Agronomy* **2023**, *13*, 1664. [[CrossRef](#)]
11. Badawy, S.A.; Zayed, B.A.; Bassiouni, S.M.A.; Mahdi, A.H.A.; Majrashi, A.; Ali, E.F.; Seleiman, M.F. Influence of Nano Silicon and Nano Selenium on Root Characters, Growth, Ion Selectivity, Yield, and Yield Components of Rice (*Oryza sativa* L.) under Salinity Conditions. *Plants* **2021**, *10*, 1657. [[CrossRef](#)] [[PubMed](#)]
12. Hawrylak-Nowak, B. Comparative Effects of Selenite and Selenate on Growth and Selenium Accumulation in Lettuce Plants under Hydroponic Conditions. *Plant Growth Regul.* **2013**, *70*, 149–157. [[CrossRef](#)]
13. Zafeiriou, I.; Gasparatos, D.; Ioannou, D.; Kalderis, D.; Massas, I. Selenium Biofortification of Lettuce Plants (*Lactuca sativa* L.) as Affected by Se Species, Se Rate, and a Biochar Co-Application in a Calcareous Soil. *Agronomy* **2022**, *12*, 131. [[CrossRef](#)]
14. Germ, M.; Kreft, I.; Stibilj, V.; Urbanc-Berčič, O. Combined Effects of Selenium and Drought on Photosynthesis and Mitochondrial Respiration in Potato. *Plant Physiol. Biochem.* **2007**, *45*, 162–167. [[CrossRef](#)] [[PubMed](#)]
15. Liu, H.; Xiao, C.; Qiu, T.; Deng, J.; Cheng, H.; Cong, X.; Cheng, S.; Rao, S.; Zhang, Y. Selenium Regulates Antioxidant, Photosynthesis, and Cell Permeability in Plants under Various Abiotic Stresses: A Review. *Plants* **2022**, *12*, 44. [[CrossRef](#)] [[PubMed](#)]
16. Habibi, G. Effect of Drought Stress and Selenium Spraying on Photosynthesis and Antioxidant Activity of Spring Barley. *Acta Agric. Slov.* **2013**, *101*, 31–39. [[CrossRef](#)]
17. Skrypnik, L.; Feduraev, P.; Golovin, A.; Maslennikov, P.; Styran, T.; Antipina, M.; Riabova, A.; Katserov, D. The Integral Boosting Effect of Selenium on the Secondary Metabolism of Higher Plants. *Plants* **2022**, *11*, 3432. [[CrossRef](#)] [[PubMed](#)]
18. Alvan, H.A.; Jabbarzadeh, Z.; Fard, J.R.; Noruzi, P. Selenium Foliar Application Alleviates Salinity Stress in Sweet William (*Dianthus barbatus* L.) by Enhancing Growth and Reducing Oxidative Damage. *Sci. Rep.* **2025**, *15*, 5570. [[CrossRef](#)] [[PubMed](#)]
19. Sun, Y.; Wang, Z.; Gong, P.; Yao, W.; Ba, Q.; Wang, H. Review on the Health-Promoting Effect of Adequate Selenium Status. *Front. Nutr.* **2023**, *10*, 1136458. [[CrossRef](#)] [[PubMed](#)]
20. Rayman, M.P. The Importance of Selenium to Human Health. *Lancet* **2000**, *356*, 233–241. [[CrossRef](#)] [[PubMed](#)]
21. Combs, G.F., Jr. Selenium in Global Food Systems. *Br. J. Nutr.* **2001**, *85*, 517–547. [[CrossRef](#)] [[PubMed](#)]

22. Estarriaga-Navarro, S.; Goicoechea, N.; Plano, D.; Sanmartín, C. Selenium Biofortification: Integrating One Health and Sustainability. *J. Sci. Food. Agric.* **2026**, *106*, 1955–1967. [[CrossRef](#)] [[PubMed](#)]
23. Ogundare, P.O.; Adefegha, S.A.; Oboh, G. Selenium Biofortification: A Sustainable Strategy to Improve Crop Quality and Human Nutrition. *J. Trace Elem. Miner.* **2026**, *16*, 100287. [[CrossRef](#)]
24. Schrauzer, G.N. Nutritional Selenium Supplements: Product Types, Quality, and Safety. *J. Am. Coll. Nutr.* **2001**, *20*, 1–4. [[CrossRef](#)] [[PubMed](#)]
25. Song, T.; Cui, G.; Su, X.; He, J.; Tong, S.; Liu, Y. The Origin of Soil Selenium in a Typical Agricultural Area in Hamatong River Basin, Sanjiang Plain, China. *Catena* **2020**, *185*, 104355. [[CrossRef](#)]
26. Feinberg, A.; Stenke, A.; Peter, T.; Hinckley, E.-L.S.; Driscoll, C.T.; Winkel, L.H.E. Reductions in the Deposition of Sulfur and Selenium to Agricultural Soils Pose Risk of Future Nutrient Deficiencies. *Commun. Earth Environ.* **2021**, *2*, 101. [[CrossRef](#)]
27. Johnson, C.C.; Fordyce, F.M.; Rayman, M.P. Factors Controlling the Distribution of Selenium in the Environment and Their Impact on Health and Nutrition. *Proc. Nutr. Soc.* **2010**, *69*, 119–132. [[PubMed](#)]
28. Fordyce, F.M.; Brereton, N.; Hughes, J.; Reay, G.; Thomas, L.; Walker, A.; Luo, W.; Lewis, J. *The Selenium Content of Scottish Soil and Food Products*; Food Standards Agency Scotland: Aberdeen, UK, 2009.
29. Finch, T.F. *Soils of Co. Limerick*; Foras Talúntais: Dublin, Ireland, 1966.
30. Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M.I. Climate Change 2021: The Physical Science Basis. *Contrib. Work. Group I Sixth Assess. Rep. Intergov. Panel Clim. Change* **2021**, *2*, 2391. [[CrossRef](#)] [[PubMed](#)]
31. Calderone, S.J.; Frankenberger, W.T., Jr.; Parker, D.R.; Karlson, U. Influence of Temperature and Organic Amendments on the Mobilization of Selenium in Sediments. *Soil Biol. Biochem.* **1990**, *22*, 615–620. [[CrossRef](#)]
32. Ye, W.; Yuan, L.; Zhu, R.; Yin, X.; Bañuelos, G. Selenium Volatilization from Tundra Soils in Maritime Antarctica. *Environ. Int.* **2021**, *146*, 106189. [[CrossRef](#)] [[PubMed](#)]
33. Rijtema, P.E. *An Analysis of Actual Evapotranspiration*; Wageningen University and Research: Wageningen, The Netherlands, 1965.
34. Winkel, L.; Vriens, B.; Jones, G.; Schneider, L.; Pilon-Smits, E.; Bañuelos, G. Selenium Cycling Across Soil-Plant-Atmosphere Interfaces: A Critical Review. *Nutrients* **2015**, *7*, 4199–4239. [[CrossRef](#)] [[PubMed](#)]
35. Moreno-Jiménez, E.; Plaza, C.; Saiz, H.; Manzano, R.; Flagmeier, M.; Maestre, F.T. Aridity and Reduced Soil Micronutrient Availability in Global Drylands. *Nat. Sustain.* **2019**, *2*, 371–377. [[CrossRef](#)] [[PubMed](#)]
36. do Nascimento, C.W.A.; da Silva, F.B.V.; Neta, A.d.B.F.; Biondi, C.M.; da Silva Lins, S.A.; de Almeida Júnior, A.B.; Preston, W. Geopedology-Climate Interactions Govern the Spatial Distribution of Selenium in Soils: A Case Study in Northeastern Brazil. *Geoderma* **2021**, *399*, 115119. [[CrossRef](#)]
37. Tolu, J.; Bouchet, S.; Helfenstein, J.; Hausheer, O.; Chékifi, S.; Frossard, E.; Tamburini, F.; Chadwick, O.A.; Winkel, L.H.E. Understanding Soil Selenium Accumulation and Bioavailability through Size Resolved and Elemental Characterization of Soil Extracts. *Nat. Commun.* **2022**, *13*, 6974. [[CrossRef](#)] [[PubMed](#)]
38. Duan, L.; Yu, Q.; Zhang, Q.; Wang, Z.; Pan, Y.; Larssen, T.; Tang, J.; Mulder, J. Acid Deposition in Asia: Emissions, Deposition, and Ecosystem Effects. *Atmos. Environ.* **2016**, *146*, 55–69. [[CrossRef](#)]
39. Carmichael, G.R.; Streets, D.G.; Calori, G.; Amann, M.; Jacobson, M.Z.; Hansen, J.; Ueda, H. Changing Trends in Sulfur Emissions in Asia: Implications for Acid Deposition, Air Pollution, and Climate. *Environ. Sci. Technol.* **2002**, *36*, 4707–4713. [[CrossRef](#)] [[PubMed](#)]
40. Hoesly, R.M.; Smith, S.J.; Feng, L.; Klimont, Z.; Janssens-Maenhout, G.; Pitkanen, T.; Seibert, J.J.; Vu, L.; Andres, R.J.; Bolt, R.M.; et al. Historical (1750–2014) Anthropogenic Emissions of Reactive Gases and Aerosols from the Community Emissions Data System (CEDS). *Geosci. Model Dev.* **2018**, *11*, 369–408. [[CrossRef](#)]
41. Gong, J.; Gao, J.; Fu, Y.; Tang, S.; Cai, Y.; Yang, J.; Wu, H.; Ma, S. Vertical Distribution and Major Influencing Factors of Soil Selenium in Tropical Climate: A Case Study of Chengmai County, Hainan Island. *Chemosphere* **2023**, *312*, 137207. [[CrossRef](#)] [[PubMed](#)]
42. Yu, T.; Yang, Z.; Lv, Y.; Hou, Q.; Xia, X.; Feng, H.; Zhang, M.; Jin, L.; Kan, Z. The Origin and Geochemical Cycle of Soil Selenium in a Se-Rich Area of China. *J. Geochem. Explor.* **2014**, *139*, 97–108. [[CrossRef](#)]
43. Reynolds, R.J.B.; Pilon-Smits, E.A.H. Plant Selenium Hyperaccumulation-Ecological Effects and Potential Implications for Selenium Cycling and Community Structure. *Biochim. Biophys. Acta-Gen. Subj.* **2018**, *1862*, 2372–2382. [[CrossRef](#)] [[PubMed](#)]
44. Guo, Q.; Ye, J.; Zeng, J.; Chen, L.; Korpelainen, H.; Li, C. Selenium Species Transforming along Soil–Plant Continuum and Their Beneficial Roles for Horticultural Crops. *Hortic. Res.* **2023**, *10*, uhac270. [[CrossRef](#)] [[PubMed](#)]
45. Wang, M.; Zhou, F.; Cheng, N.; Chen, P.; Ma, Y.; Zhai, H.; Qi, M.; Liu, N.; Liu, Y.; Meng, L. Soil and Foliar Selenium Application: Impact on Accumulation, Speciation, and Bioaccessibility of Selenium in Wheat (*Triticum aestivum* L.). *Front. Plant Sci.* **2022**, *13*, 988627. [[CrossRef](#)] [[PubMed](#)]

46. Luo, H.; Du, B.; He, L.; Zheng, A.; Pan, S.; Tang, X. Foliar Application of Sodium Selenate Induces Regulation in Yield Formation, Grain Quality Characters and 2-Acetyl-1-Pyrroline Biosynthesis in Fragrant Rice. *BMC Plant Biol.* **2019**, *19*, 502. [[CrossRef](#)] [[PubMed](#)]
47. Schiavon, M.; Berto, C.; Malagoli, M.; Trentin, A.; Sambo, P.; Dall'Acqua, S.; Pilon-Smits, E.A.H. Selenium Biofortification in Radish Enhances Nutritional Quality via Accumulation of Methyl-Selenocysteine and Promotion of Transcripts and Metabolites Related to Glucosinolates, Phenolics, and Amino Acids. *Front. Plant Sci.* **2016**, *7*, 1371. [[CrossRef](#)] [[PubMed](#)]
48. Zhou, Y.; Nie, K.; Geng, L.; Wang, Y.; Li, L.; Cheng, H. Selenium's Role in Plant Secondary Metabolism: Regulation and Mechanistic Insights. *Agronomy* **2024**, *15*, 54. [[CrossRef](#)]
49. Abdullah; Wani, K.I.; Hayat, K.; Naeem, M.; Aftab, T. Multifaceted Role of Selenium in Plant Physiology and Stress Resilience: A Review. *Plant Sci.* **2025**, *355*, 112456. [[CrossRef](#)] [[PubMed](#)]
50. Gaucin-Delgado, J.M.; Hernandez-Montiel, L.G.; Sanchez-Chavez, E.; Ortega-Ortiz, H.; Fortis-Hernandez, M.; Reyes-Pérez, J.J.; Preciado-Rangel, P. Agronomic Biofortification with Selenium Improves the Yield and Nutraceutical Quality in Tomato under Soilless Conditions. *Not. Bot. Horti Agrobot.* **2020**, *48*, 1221–1232. [[CrossRef](#)]
51. Mrština, T.; Praus, L.; Száková, J.; Kaplan, L.; Tlustoš, P. Foliar Selenium Biofortification of Soybean: The Potential for Transformation of Mineral Selenium into Organic Forms. *Front. Plant Sci.* **2024**, *15*, 1379877. [[CrossRef](#)] [[PubMed](#)]
52. Deliboran, A. Selenium Biofortification of Grain Maize through Foliar Application of Sodium Selenate: Selenium Accumulation and Recovery by the Grain. *Commun. Soil Sci. Plant Anal.* **2023**, *54*, 1564–1581. [[CrossRef](#)]
53. Shah, T.; Alahmadi, T.A.; Ansari, M.J.; Khan, Z.; Khan, H. Agro-Biofortification of Maize with Selenium for Higher Grain Selenium Contents and Productivity. *S. Afr. J. Bot.* **2024**, *168*, 253–259. [[CrossRef](#)]
54. Zhang, H.; Zhao, Z.; Zhang, X.; Zhang, W.; Huang, L.; Zhang, Z.; Yuan, L.; Liu, X. Effects of Foliar Application of Selenate and Selenite at Different Growth Stages on Selenium Accumulation and Speciation in Potato (*Solanum tuberosum* L.). *Food Chem.* **2019**, *286*, 550–556. [[CrossRef](#)] [[PubMed](#)]
55. Li, Y.; Xiao, Y.; Hao, J.; Fan, S.; Dong, R.; Zeng, H.; Liu, C.; Han, Y. Effects of Selenate and Selenite on Selenium Accumulation and Speciation in Lettuce. *Plant Physiol. Biochem.* **2022**, *192*, 162–171. [[CrossRef](#)] [[PubMed](#)]
56. Hall, J.A.; Bobe, G.; Filley, S.J.; Bohle, M.G.; Pirelli, G.J.; Wang, G.; Davis, T.Z.; Bañuelos, G.S. Impact of Selenium Biofortification on Production Characteristics of Forages Grown Following Standard Management Practices in Oregon. *Front. Plant Sci.* **2023**, *14*, 1121605. [[CrossRef](#)] [[PubMed](#)]
57. Preciado-Rangel, P.; Hernández-Montiel, L.G.; Valdez-Cepeda, R.D.; de la Cruz-Lázaro, E.; Lara-Capistrán, L.; Morales-Morales, B.; Gaucin-Delgado, J.M. Biofortification with Selenium Increases Bioactive Compounds and Antioxidant Capacity in Tomato Fruits. *Terra Latinoam.* **2021**, *39*, 1–10. [[CrossRef](#)]
58. Hu, Q.; Xu, J.; Pang, G. Effect of Selenium on the Yield and Quality of Green Tea Leaves Harvested in Early Spring. *J. Agric. Food Chem.* **2003**, *51*, 3379–3381. [[CrossRef](#)] [[PubMed](#)]
59. Tian, M.; Yang, Y.; Ávila, F.W.; Fish, T.; Yuan, H.; Hui, M.; Pan, S.; Thannhauser, T.W.; Li, L. Effects of Selenium Supplementation on Glucosinolate Biosynthesis in Broccoli. *J. Agric. Food Chem.* **2018**, *66*, 8036–8044. [[CrossRef](#)] [[PubMed](#)]
60. Rao, S.; Gou, Y.; Yu, T.; Cong, X.; Gui, J.; Zhu, Z.; Zhang, W.; Liao, Y.; Ye, J.; Cheng, S. Effects of Selenate on Se, Flavonoid, and Glucosinolate in Broccoli Florets by Combined Transcriptome and Metabolome Analyses. *Food Res. Int.* **2021**, *146*, 110463. [[CrossRef](#)] [[PubMed](#)]
61. Buttarelli, M.S.; Céccoli, G.; Trod, B.S.; Stoffel, M.M.; Simonutti, M.; Bouzo, C.A.; Turowski, V.R.; Perez, A.A.; Llugany, M.; Sánchez-Martín, M.-J. Enhancing Nutritional and Functional Properties of Broccoli Leaves Through Selenium Biofortification: Potential for Sustainable Agriculture and Bioactive Compound Valorization. *Agronomy* **2025**, *15*, 389. [[CrossRef](#)]
62. Li, L.; Liu, Q.; Luo, L.; Wu, S.; Chen, C.; Yin, C. Optimizing Selenium Biofortification in Camellia Sinensis: A Meta-Analysis of Fertilization Strategies, Cultivar Selection, and Harvest Timing on Tea Se Accumulation and Quality. *Food Res. Int.* **2025**, *221*, 117400. [[CrossRef](#)] [[PubMed](#)]
63. Silva, M.A.; de Sousa, G.F.; Van Opbergen, G.A.Z.; Van Opbergen, G.G.A.Z.; Corguinha, A.P.B.; Bueno, J.M.M.; Brunetto, G.; Leite, J.M.; dos Santos, A.A.; Lopes, G. Foliar Application of Selenium Associated with a Multi-Nutrient Fertilizer in Soybean: Yield, Grain Quality, and Critical Se Threshold. *Plants* **2023**, *12*, 2028. [[CrossRef](#)] [[PubMed](#)]
64. Danso, O.P.; Asante-Badu, B.; Zhang, Z.; Song, J.; Wang, Z.; Yin, X.; Zhu, R. Selenium Biofortification: Strategies, Progress and Challenges. *Agriculture* **2023**, *13*, 416. [[CrossRef](#)]
65. Ahmad, A.; Javad, S.; Iqbal, S.; Shahzadi, K.; Gatasheh, M.K.; Javed, T. Alleviation Potential of Green-Synthesized Selenium Nanoparticles for Cadmium Stress in *Solanum lycopersicum* L: Modulation of Secondary Metabolites and Physiochemical Attributes. *Plant Cell Rep.* **2024**, *43*, 113. [[CrossRef](#)] [[PubMed](#)]
66. Nawaz, F.; Ashraf, M.Y.; Ahmad, R.; Waraich, E.A.; Shabbir, R.N.; Hussain, R.A. Selenium Supply Methods and Time of Application Influence Spring Wheat (*Triticum aestivum* L.) Yield under Water Deficit Conditions. *J. Agric. Sci.* **2017**, *155*, 643–656. [[CrossRef](#)]

67. Desouky, A.F.; Desoukey, S.F.; Abdel-Aziz, H.S.M.; EL-kholy, R.I.; Hanafy, M.S. Exogenous Application of Selenium Nanoparticles (Se-NPs) to Mitigate Salt Stress in Soybean-Evaluation of Physiological, Molecular and Biochemical Processes. *J. Soil Sci. Plant Nutr.* **2024**, *24*, 6798–6813. [\[CrossRef\]](#)
68. Ghouri, F.; Ali, Z.; Naeem, M.; Ul-Allah, S.; Babar, M.; Baloch, F.S.; Chattah, W.S.; Shahid, M.Q. Effects of Silicon and Selenium in Alleviation of Drought Stress in Rice. *Silicon* **2022**, *14*, 5453–5461. [\[CrossRef\]](#)
69. 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. [\[CrossRef\]](#) [\[PubMed\]](#)
70. Liao, Q.; Xing, Y.; Li, A.-M.; Liang, P.-X.; Jiang, Z.-P.; Liu, Y.-X.; Huang, D.-L. Enhancing Selenium Biofortification: Strategies for Improving Soil-to-Plant Transfer. *Chem. Biol. Technol. Agric.* **2024**, *11*, 148. [\[CrossRef\]](#)
71. Zhu, C.; Hao, S.; Liu, C.; Wang, Y.; Jia, X.; Xu, J.; Guo, S.; Huo, J.; Wang, W. An Efficient Computer Vision-Based Dual-Face Target Precision Variable Spraying Robotic System for Foliar Fertilisers. *Agronomy* **2024**, *14*, 2770. [\[CrossRef\]](#)
72. Dong, G.; Lou, X.; Wang, H. Towards Robust UAV Navigation in Agriculture: Key Technologies, Application, and Future Directions. *Plants* **2026**, *15*, 1303. [\[CrossRef\]](#) [\[PubMed\]](#)
73. Burmistrov, D.E.; Shumeyko, S.A.; Semenova, N.A.; Dorokhov, A.S.; Gudkov, S.V. Selenium Nanoparticles (Se NPs) as Agents for Agriculture Crops with Multiple Activity: A Review. *Agronomy* **2025**, *15*, 1591. [\[CrossRef\]](#)
74. Sowmya, R.; Namasivayam, S.K.R.; Sivasuriyan, K.S.; Varshan, G. S, A.; Samrat, K. Selenium Nanoparticles and Nanocomposites in Sustainable Agriculture: Synthesis, Stress Alleviation Mechanisms, and Soil Health Impacts. *Plant Nano Biol.* **2026**, *15*, 100240. [\[CrossRef\]](#)
75. Sampath, S.; Sunderam, V.; Manjusha, M.; Dlamini, Z.; Lawrance, A.V. Selenium Nanoparticles: A Comprehensive Examination of Synthesis Techniques and Their Diverse Applications in Medical Research and Toxicology Studies. *Molecules* **2024**, *29*, 801. [\[CrossRef\]](#) [\[PubMed\]](#)
76. Kikkert, J.; Berkelaar, E. Plant Uptake and Translocation of Inorganic and Organic Forms of Selenium. *Arch. Environ. Contam. Toxicol.* **2013**, *65*, 458–465. [\[CrossRef\]](#) [\[PubMed\]](#)
77. Schiavon, M.; Nardi, S.; Dalla Vecchia, F.; Ertani, A. Selenium Biofortification in the 21st Century: Status and Challenges for Healthy Human Nutrition. *Plant Soil* **2020**, *453*, 245–270. [\[CrossRef\]](#) [\[PubMed\]](#)
78. Bañuelos, G.S.; Arroyo, I.; Pickering, I.J.; Yang, S.I.; Freeman, J.L. Selenium Biofortification of Broccoli and Carrots Grown in Soil Amended with Se-Enriched Hyperaccumulator *Stanleya pinnata*. *Food Chem.* **2015**, *166*, 603–608. [\[CrossRef\]](#) [\[PubMed\]](#)
79. Tiganescu, E.; Safinazlou, S.; Abdin, A.Y.; Lilischkis, R.; Schäfer, K.-H.; Fink-Straube, C.; Nasim, M.J.; Jacob, C. Selenium Disulfide from Sustainable Resources: An Example of “Redneck” Chemistry with a Pinch of Salt. *Materials* **2024**, *17*, 5733. [\[CrossRef\]](#)
80. Sarathchandra, S.U.; Watkinson, J.H. Oxidation of Elemental Selenium to Selenite by *Bacillus megaterium*. *Science* **1981**, *211*, 600–601. [\[CrossRef\]](#) [\[PubMed\]](#)
81. Dong, S.; Zhang, B.; Wang, Z.; Zhou, X.; Gao, Q. Responses of Soil Bacterial Communities and Maize Yields to Sulfur Application across Four Soil Types. *Front. Microbiol.* **2024**, *15*, 1329938. [\[CrossRef\]](#) [\[PubMed\]](#)
82. Tiganescu, E.; Abdin, A.Y.; Razouk, A.; Nasim, M.J.; Jacob, C. The Redox Riddle of Selenium Sulfide. *Curr. Opin. Chem. Biol.* **2023**, *76*, 102365. [\[CrossRef\]](#) [\[PubMed\]](#)
83. Rayman, M.P.; Infante, H.G.; Sargent, M. Food-Chain Selenium and Human Health: Spotlight on Speciation. *Br. J. Nutr.* **2008**, *100*, 238–253. [\[CrossRef\]](#) [\[PubMed\]](#)
84. Mutonhodza, B.; Joy, E.J.M.; Bailey, E.H.; Lark, M.R.; Kangara, M.G.M.; Broadley, M.R.; Matsungu, T.M.; Chopera, P. Linkages between Soil, Crop, Livestock, and Human Selenium Status in SUB-SAHARAN Africa: A Scoping Review. *Int. J. Food Sci. Technol.* **2022**, *57*, 6336–6349. [\[CrossRef\]](#) [\[PubMed\]](#)
85. Ferreira, R.L.U.; Sena-Evangelista, K.C.M.; De Azevedo, E.P.; Pinheiro, F.I.; Cobucci, R.N.; Pedrosa, L.F.C. Selenium in Human Health and Gut Microflora: Bioavailability of Selenocompounds and Relationship with Diseases. *Front. Nutr.* **2021**, *8*, 685317. [\[CrossRef\]](#) [\[PubMed\]](#)
86. Dinh, Q.T.; Cui, Z.; Huang, J.; Tran, T.A.T.; Wang, D.; Yang, W.; Zhou, F.; Wang, M.; Yu, D.; Liang, D. Selenium Distribution in the Chinese Environment and Its Relationship with Human Health: A Review. *Environ. Int.* **2018**, *112*, 294–309. [\[CrossRef\]](#) [\[PubMed\]](#)
87. Stoffaneller, R.; Morse, N. A Review of Dietary Selenium Intake and Selenium Status in Europe and the Middle East. *Nutrients* **2015**, *7*, 1494–1537. [\[CrossRef\]](#) [\[PubMed\]](#)
88. Mpeketula, P.; Mazibuko, D.M.; Gono, H.; Fiwa, L.; Maskey, S.; Okazawa, H. Evaluation of Soil Micronutrients Across Selected Land Use Types in Chembe Enclave Village, Lake Malawi National Park. *Int. J. Environ. Rural Dev.* **2024**, *15*, 136–142.
89. Oklo, A.D.; Sha’Ato, R.; Eneji, I.S.; Igyor, M.A. Levels of Selenium in Vegetables, Medicinal Plants and Soils from Selected Sites within the Lower Benue River Basin Development Authority Catchment, Nigeria. *IOSR J. Environ. Sci. Toxicol. Food Technol.* **2017**, *11*, 21–30. [\[CrossRef\]](#)
90. Ligowe, I.S.; Phiri, F.P.; Ander, E.L.; Bailey, E.H.; Chilimba, A.D.C.; Gashu, D.; Joy, E.J.M.; Lark, R.M.; Kabambe, V.; Kalimpira, A.A. Selenium Deficiency Risks in Sub-Saharan African Food Systems and Their Geospatial Linkages. *Proc. Nutr. Soc.* **2020**, *79*, 457–467. [\[CrossRef\]](#) [\[PubMed\]](#)

91. Adeniyi, M.J.; Agoreyo, F.O. Nigeria and the Selenium Micronutrient: A Review. *Ann. Med. Health Sci. Res.* **2018**, *8*, 5–11.
92. Mutonhodza, B.; Chagumaira, C.; Dembedza, M.P.; Joy, E.J.M.; Manzeke-Kangara, M.G.; Njovo, H.; Nyadzayo, T.K.; Lark, R.M.; Kalimpira, A.A.; Bailey, E.H. A Pilot Survey of Selenium Status and Its Geospatial Variation among Children and Women in Three Rural Districts of Zimbabwe. *Front. Nutr.* **2023**, *10*, 1235113. [[CrossRef](#)] [[PubMed](#)]
93. Belay, A.; Joy, E.J.M.; Chagumaira, C.; Zerfu, D.; Ander, E.L.; Young, S.D.; Bailey, E.H.; Lark, R.M.; Broadley, M.R.; Gashu, D. Selenium Deficiency Is Widespread and Spatially Dependent in Ethiopia. *Nutrients* **2020**, *12*, 1565. [[CrossRef](#)] [[PubMed](#)]
94. Röllin, H.B.; Channa, K.; Olutola, B.; Odland, J.Ø. Selenium Status, Its Interaction with Selected Essential and Toxic Elements, and a Possible Sex-Dependent Response in Utero, in a South African Birth Cohort. *Int. J. Environ. Res. Public Health* **2021**, *18*, 8344. [[CrossRef](#)] [[PubMed](#)]
95. Chilala, P.; Skalickova, S.; Horky, P. Selenium Status of Southern Africa. *Nutrients* **2024**, *16*, 975. [[CrossRef](#)] [[PubMed](#)]
96. Junior, E.C.S.; Wadt, L.H.d.O.; Silva, K.E.; Lima, R.M.B.; Batista, K.D.; Guedes, M.C.; Carvalho, G.S.; Carvalho, T.S.; Reis, A.R.; Lopes, G. Natural Variation of Selenium in Brazil Nuts and Soils from the Amazon Region. *Chemosphere* **2017**, *188*, 650–658. [[CrossRef](#)] [[PubMed](#)]
97. da Silva Junior, E.C.; de Oliveira Wadt, L.H.; da Silva, K.E.; de Lima, R.M.B.; Batista, K.D.; Guedes, M.C.; de Oliveira Junior, R.C.; Dos Reis, A.R.; Lopes, G.; Broadley, M.R. Geochemistry of Selenium, Barium, and Iodine in Representative Soils of the Brazilian Amazon Rainforest. *Sci. Total Environ.* **2022**, *828*, 154426. [[CrossRef](#)] [[PubMed](#)]
98. Lemire, M.; Philibert, A.; Fillion, M.; Passos, C.J.S.; Guimarães, J.R.D.; Barbosa, F., Jr.; Mergler, D. No Evidence of Selenosis from a Selenium-Rich Diet in the Brazilian Amazon. *Environ. Int.* **2012**, *40*, 128–136. [[CrossRef](#)] [[PubMed](#)]
99. Hartikainen, H. Biogeochemistry of Selenium and Its Impact on Food Chain Quality and Human Health. *J. Trace Elem. Med. Biol.* **2005**, *18*, 309–318. [[CrossRef](#)] [[PubMed](#)]
100. Poppy, G.M.; Baverstock-Poppy, J.J.; Baverstock, J. Trade and Dietary Preferences Can Determine Micronutrient Security in the United Kingdom. *Nat. Food* **2022**, *3*, 512–522. [[CrossRef](#)] [[PubMed](#)]
101. Filippini, T.; Cilloni, S.; Malavolti, M.; Violi, F.; Malagoli, C.; Tesauro, M.; Bottecchi, I.; Ferrari, A.; Vescovi, L.; Vinceti, M. Dietary Intake of Cadmium, Chromium, Copper, Manganese, Selenium and Zinc in a Northern Italy Community. *J. Trace Elem. Med. Biol.* **2018**, *50*, 508–517. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.