

Review Article

A double-edged sword: Biofortifying fruit crops with Selenium nanoparticles

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ABSTRACT

Selenium (Se) is an essential trace element for humans, impacting multiple key physiological processes in fruit crops, including secondary metabolism and ripening. Among different methods applied, literature provides evidence of the effectiveness and safety of applying selenium nanoparticles (SeNPs) as a tool for plant biofortification. SeNPs are typically biologically or chemically produced 2-282 nm particles of elemental Se (Se⁰) coated with an organic membrane, with unique physicochemical properties, often allowing them to be less toxic and more bioavailable compared to mineral Se. The biofortification of fruit crops with SeNPs has not been extensively reviewed. The aim of this work is to identify specific and common trends in the effects of SeNPs application across different fruit crops. SeNPs applied at concentrations of up to 50 mg L⁻¹ in irrigation or up to 100 mg L⁻¹ as foliar spraying showed, in general, positive effects on growth, yield, nutraceutical value, biochemical composition, antioxidative state, improved responses to abiotic stresses in tomato, cucumber, strawberry, physalis, persimmon, orange, lime, grape, pomegranate, apple, mango, date, and pepper. In the latest, SeNPs increased the yield up to 53%, and phenols up to 75%. SeNPs enhanced drought, heat, and salinity resistance, activated defense-related mechanisms by upregulating lipoxygenase (LOX), phenylalanine lyase (PAL), β-1,3-glucanase (GLU), superoxide dismutase (SOD), and reduced Reactive Oxygen Species (ROS). In addition to that, postharvest spraying, submerging, or coating fruit in up to 150 mg L⁻¹ SeNPs resulted in inhibition of bacterial, and fungal pathogens, including *Alternaria spp.*, *Botrytis spp.*, *Fusarium spp.*, and nematodes *Meloidogyne spp.*

1. Introduction

Selenium (Se) is an essential trace element for human health, and as a part of selenoproteins, it is vital for antioxidant defense, immune function, and thyroid regulation (Bai et al. 2025). Se deficiency is one of the most challenging types of malnutrition to diagnose, affecting approximately one billion people worldwide (dos Reis et al. 2017). As an «essential poison», selenium has a narrow range of dietary intake, making it difficult to design a food supplement that is both effective and safe (Sun et al. 2023). Humans may fulfill their dietary needs of Se from both plant-based and animal-based foods. The importance of supplementing the human diet with Se has been extensively discussed in the reviews by Newman et al. (2019) and Lei et al. (2022).

Studies claim that animal-based products provide more consistent Se

dietary intake due to the homeostasis mechanisms that regulate Se accumulation in animal tissues (Lei et al. 2022). In contrast, the Se amount in plants growing in open fields is more variable and is influenced by the Se content of the soil. For example, in Brazil nuts, which are known as a rich natural source of dietary Se (Thomson et al. 2008), the Se amount in a 100 g serving can vary from 136 to 2740 µg Se across 15 samples (a 20-fold difference). In comparison, an equal serving of tuna fish contains between 61.9 to 221 µg Se across 11 samples (a 3.5-fold difference), according to USDA (2024).

Consuming any plant-based products derived from the species capable of accumulating higher amounts of Se does not necessarily guarantee an increase in dietary Se uptake. However, the absence - or low performance - of homeostatic mechanisms capable of balancing the Se content in plant tissues makes plants a better carrier for delivering

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elevated Se levels in the diet, thus offering a stronger foundation for the development of nutraceutical products. Plant-based nutraceutical products provide an opportunity to fill the dietary gap by offering consumers organic and, therefore, more bioavailable forms of selenium, such as Se-methionine and Se-cysteine, which are derived from less bioavailable mineral forms of Se, such as selenite and selenate.

A recent book edited by [Hasanuzzaman et al. \(2023\)](#) comprehensively summarizes the contemporary state of the art of mineral biofortification in crop plants. Selenium (Se) biofortification is discussed in two chapters, which report current findings on the efficiency of Se enrichment for overcoming dietary deficiency with particular attention to the interface between nutrition and human health ([Albadrani et al. 2023](#)) and enriching crops with Se in the form of Se salts and Se nanoparticles (SeNPs) ([Rasheed et al. 2023](#)). However, the results discussed by the authors exclusively focus on cereal crops: wheat, barley, maize, and rice.

The main advantage of SeNPs is the possibility to use elemental Se (Se^0) as a more sustainable alternative to the highly reactive and potentially toxic sodium selenite and sodium selenate. Thanks to the electromagnetic charge of their coating layer, SeNPs enable the transport of otherwise unabsorbable elemental selenium into plants via the xylem flow and following incorporation into organic molecules. Considering that the use of NPs is interesting for their bioavailability and sustainability, we are interested in completing the set of information provided by the book of [Hasanuzzaman et al. \(2023\)](#) with a focus on SeNPs and fruit crops, also considering that [D'Amato et al. \(2020\)](#), already published a paper on fruit crops and selenium salts, reporting a complex and variable set of possible effects. In agricultural crops, several beneficial effects of SeNPs have been reported. SeNPs can enhance plant growth and nutrient uptake, as well as strengthen plant immune systems, thereby improving resistance to pests and diseases more effectively than conventional forms of selenium ([Garza-García et al. 2021](#)).

2. Scope and limitations

SeNPs are the tiny particles of (typically) elementary Se, ranging from 2 to 282 nm in diameter ([Hernández-Hernández et al. 2019](#); [Nogueira et al. 2024](#)). They may be produced using chemical reduction, biological methods (implying plant extracts, microorganisms, or enzymes), or, less often, using physical techniques (such as laser ablation). Due to their nano size and large surface area, they show unique physical, chemical, and biological properties compared to bulk Se. SeNPs can be synthesized with differences in terms of size, shape, color, surface area, true density, crystallinity, degree of crystallinity, and stability (ζ -potential, describing the tendency of NPs to agglomerate in the suspension depending on the surface electrical potential of the NPs): all these parameters may affect the efficacy of the treatment.

The main constraint is the limited stability, which can reduce SeNPs' effectiveness over time in agricultural applications; stability may depend on storage conditions, coating, and matrix ([Bulgarini et al. 2021](#)).

Contemporary literature reports Se nanoparticles as an alternative to sodium selenate in fruit biofortification ([Shiriaev et al. 2022](#)). The efficiency of NPs in delivering Se in plant organs, along with the regulatory and physiological consequences, is then compared with the corresponding effects of sodium selenate. This may lead readers to believe that NPs represent a single chemo-physical form of Se. However, SeNPs do not represent a single chemo-physical form of Se. Se enrichment largely depends on the characteristics of the applied NPs, including the coating composition. For example, biogenic SeNPs are covered by a complex organic cap consisting of different biomolecules, such as proteins, lipids, and carbohydrates, that are specific to the bacterial strain used in the bioreactor ([Cremonini et al. 2018](#)). In contrast, chemically synthesized SeNPs are coated with a simpler layer such as L-cysteine ([Shiriaev et al. 2022](#)). As a result, the produced SeNPs may have

different sizes, stability, and surface charge. These parameters inevitably affect the efficacy of SeNPs in entering plant tissues and translocating within them.

In this review, two methodological criteria have been compared: typology of SeNPs (shape, size, and synthesis protocol) and the treatment methodology (treated plant part, phenological stage, and number of performed treatments). It must be anticipated that one of the limitations of the present work is the incomplete output and set of information of the sources: authors focusing on biological and biochemical aspects often neglect to thoroughly report technical details, which are essential for replicating their study or comparing it with different approaches.

3. Effects of type and application method of SeNPs on selenium content, yield, and fruit characteristics in fruit crops

One of the most studied model fruit species treated with SeNPs is tomato. This is due not only to the practical convenience of using tomato as an experimental model, but also to its potential as a nutraceutical product, capable of delivering organic Se when consumed fresh.

[Hernández-Hernández et al. \(2019\)](#) reported five substrate applications of spherical, 2-20 nm SeNPs at concentrations of 1, 10, and 20 mg L⁻¹ every 15 days starting at 11 days after transplanting. They observed an increase in the yield of up to 21% with 10 mg L⁻¹. Additionally, they detected improvements in fruit quality and composition, including increased vitamin C, glutathione, flavonoids, firmness, total soluble solids, and titratable acidity. [Neysanian et al. \(2020\)](#) used slightly larger NPs (10-40 nm), also in this case applied multiple times. However, unlike [Hernández-Hernández et al. \(2019\)](#), they used foliar spray to deliver Se: 37-day-old seedlings were sprayed six times at one-week intervals with 0, 3, and 10 mg L⁻¹ Se NPs. They observed that the 3 mg L⁻¹ treatment increased fruit number (25.3%) and fresh mass (18%). All treatments at all applied concentrations improved fruit postharvest longevity by 38%. The 3 mg L⁻¹ treatment also improved Mg, Fe, and Zn concentration in fruit. The 10 mg L⁻¹ treatment increased H₂O₂ accumulation and lipid peroxidation levels. Noticeably, the 10 mg L⁻¹ treatment caused toxicity and reduced fruit production by 39.5% and fruit fresh weight. These results may suggest that foliar spraying is more effective in delivering SeNPs in plants compared to substrate supplementation. Nevertheless, this comparison relies only on an indirect conclusion, specifically comparing the effect of accumulated Se, since [Hernández-Hernández et al. \(2019\)](#) do not report the concentration of Se in the plant. In our experiments performed on tomato cv Microtom, after 2 and 4 foliar sprays from plantula to Immature green stage with 20 mg L⁻¹ biogenic SeNPs, mature fruit accumulated up to 1.5 and 2 mg Se kg⁻¹ DW, respectively; however, a single application of the same type of SeNPs resulted in a low Se accumulation in fruit, statistically not different from control ([Shiriaev et al. 2025](#), unpublished).

[Neysanian et al. \(2020\)](#) reported an amount of Se detected in tomato fruit after applying 6 weekly sprayings of up to 10 mg L⁻¹ SeNPs, which is six times lower than the amount found by our research group ([Shiriaev et al. 2022](#)) in tomatoes sprayed only once with the same concentration of SeNPs (e.g., 0.12 vs 0.68 mg kg⁻¹ DW). In this comparison, multiple applications of SeNPs result in a lower uptake compared to a single treatment. This may be hypothetically explained by the use of different tomato genotypes and different types of NPs (in terms of size and synthesis protocol), leading to different velocities of Se transport in plant tissues, as well as by the phenological phase when the treatment is performed. However, holistically reviewing all available literature, multiple treatments have been used more frequently than single treatments in Se biofortification of tomatoes and other fruit crops ([Fig. 1](#), Supplementary material Table S1).

Noticeably, SeNPs impact is often not directly proportional to the concentration applied. For example, [Reyes-Pérez et al. \(2025\)](#) sprayed transplanted tomato plants with 5, 15, and 30 mg L⁻¹ 80 nm SeNPs and reported increases in chlorophyll content of 11.1, 18.2, and 15.2%,

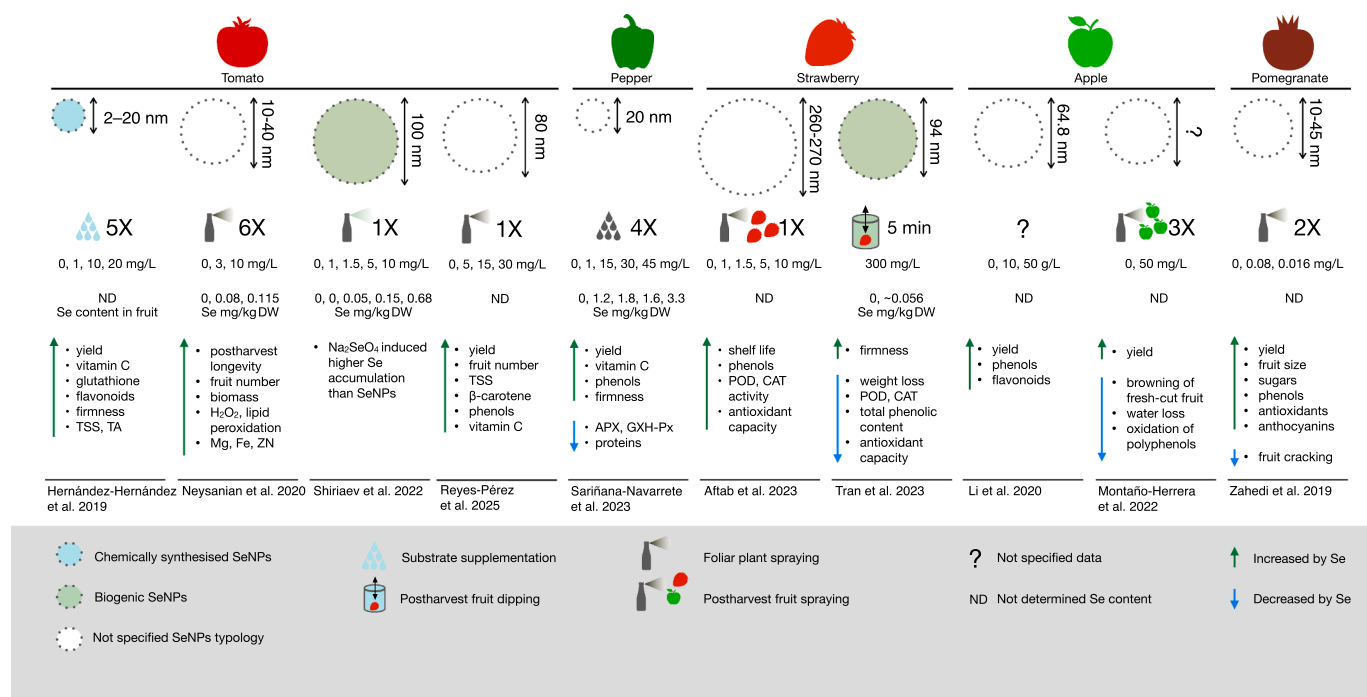


Fig. 1. Schematic diagram summarizing the effects of SeNP type and application method on selenium content, yield, and fruit characteristics in different fruit crops. The applied Se concentration is expressed in mg/L, and the Se content detected in fruit tissue is expressed in mg/kg DW. The symbols color corresponds to the type of NPs while symbols shape represents the treatment method.

respectively, and in β -Carotene of 10.9, 50.8, and 17.6%, respectively. The most effective dose in terms of influencing fruit composition was 15 mg L⁻¹ 80 nm SeNPs. However, based on yield and quality parameters, the lowest dose (5 mg L⁻¹ 80 nm SeNPs) led to increases in fruit number size, vitamin C content and TSS.

The use of SeNPs to biofortify fruit has been studied in several other fruit species.

Sariñana-Navarrete et al. (2023) treated Jalapeño pepper with up to 45 mg L⁻¹ SeNPs four times via roots, resulting in up to 3 mg kg⁻¹ DW Se. SeNPs increased pepper yield by up to 52.75%, increased vitamin C content and total phenols, and upregulated the activity of peroxidases. Peroxidase activity was also increased in strawberries sprayed with up to 30 mM (2370 mg L⁻¹) SeNPs solution (Aftab et al. 2023), indicating that SeNPs induce a stress response in plant tissues. SeNPs also increased the production of phenols and antioxidant capacity, ultimately extending the shelf-life of treated strawberries. Another off-plant SeNPs application has been reported by Tran et al. (2023), who submerged harvested strawberries in a colloidal solution to form a layer of SeNPs after drying. They reported that the application of a 300 mg L⁻¹ SeNPs solution caused an accumulation of Se up to 0.56 μ g/100 g FW after coating (approximately 56 mg kg⁻¹ DW). The Se coating enhanced the firmness of strawberries by 26% and reduced weight loss threefold. However, without data on Se speciation inside tissues, interpreting such results from a safety perspective might be challenging.

Se NPs were also applied to fruit-bearing woody species. Zahedi et al. (2019b) sprayed pomegranate plants with SeNPs twice: once at blooming and again one month later. They observed an increase in fruit number, indicating a positive effect on yield, as well as compositional changes in the fruit, including increased total sugars, phenolic compounds, antioxidants, and anthocyanins. Notably, they used one of the lowest concentrations reported in literature: 1 and 2 μ M SeNPs (~0.8-0.16 mg L⁻¹). In apples, three foliar SeNPs applications at 50 mg L⁻¹ SeNPs also improved the yield and increased the synthesis of phenols and flavonoids in the fruit (Montaña-Herrera et al. 2022). Another study reported that SeNPs delayed the browning of fresh-cut apples, prevented the oxidation of polyphenols, and reduced water loss (Li et al.

2020).

We can assume that SeNPs application is a versatile tool for biofortifying fruit crops with Se. Se, delivered in the form of SeNPs, has the potential to increase yield, reduce tissue decay, and boost the production of antioxidants, including phenolic compounds. The physiological and biochemical changes observed in different fruit species suggest that SeNPs may induce a stress response, resulting in an increase in antioxidant compounds.

Nevertheless, it is challenging to provide a complete comparison of different SeNPs and their effectiveness in delivering Se in fruit, as a significant portion of the published papers (Zahedi et al. 2019b; Hernández-Hernández et al. 2019; Montaña-Herrera et al. 2022; Aftab et al. 2023) either do not quantify or do not report the results of Se analysis in the investigated material.

4. SeNPs and abiotic stress responses

SeNPs enrichment has often been discussed not only for its direct impact on the nutraceutical status of edible plant parts, but also to mitigate the effects of abiotic stresses. The relevant literature frequently highlights salinity and drought as the primary stress factors that SeNPs-treated plants can withstand (Fig. 2, Supplementary material Table S2).

4.1. Salinity

Morales-Espinoza et al. (2019) performed five substrate applications of up to 20 mg L⁻¹ SeNPs on tomatoes. They revealed that SeNPs helped compensate for the negative effects of NaCl salinity stress on yield by increasing the weight of fruit per plant by 13% and improving fruit quality through a rise in fruit titratable acidity. They also observed a positive correlation between SeNPs treatment and photosynthesis, based on the increased chlorophylls a and b content, which was increased by 71% and 120%, respectively, compared to the NaCl-only treatment. In a similarly designed experiment, González-García et al. (2021) added SeNPs to the substrate of bell pepper plants stressed with 25 and 50 mM NaCl. They reported that SeNPs negatively impacted phenol levels in

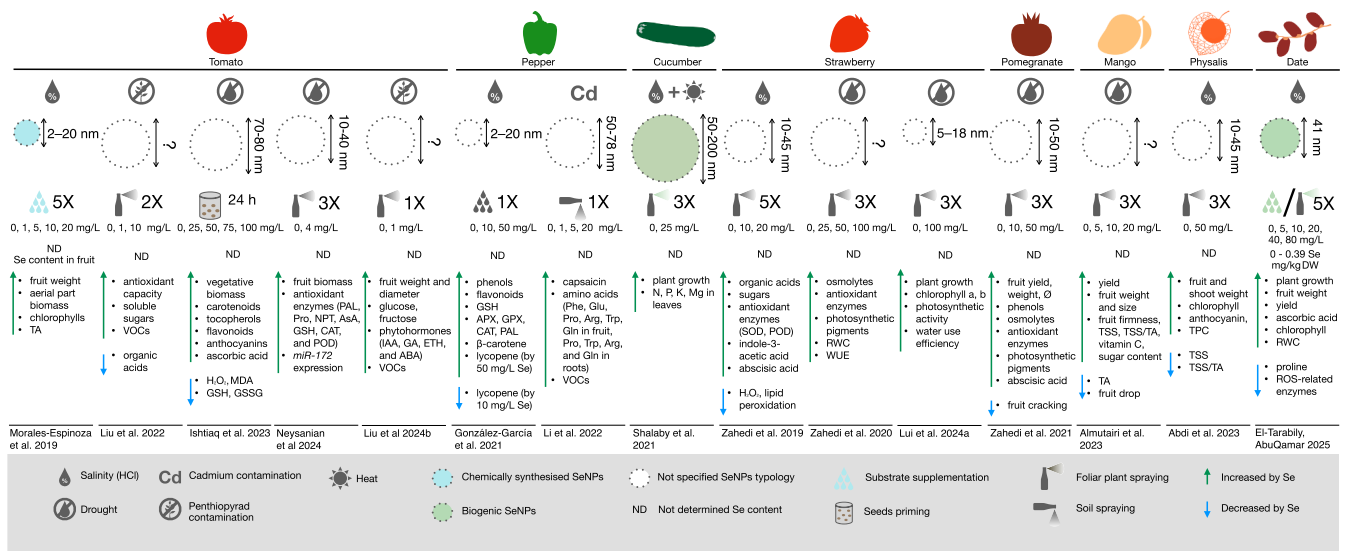


Fig. 2. Effects of SeNP type and application method on Se content, yield, and fruit characteristics in crops subjected to different abiotic stresses. The applied Se concentration is expressed in mg/L, and the Se content detected in fruit tissue is expressed in mg/kg DW. The symbols color corresponds to the type of NPs while symbols shape represents the treatment method.

fruit but increased phenol content in leaves. SeNPs also boosted levels of flavonoids, GSH, β -carotene, and yellow carotenoids in leaves while upregulating APX, GPX, CAT, and PAL activity.

Elevated activity of antioxidant enzymes was also observed in strawberry plants grown on up to 75 mM NaCl saline soil and foliarly sprayed five times with SeNPs at concentrations of 10 and 20 mg L⁻¹ every week starting one week after applying salt stress (Zahedi et al. 2019a). These authors also reported that, in response to SeNPs under stress, fruit produced higher levels of amino acids and sugars and emitted more stress-signaling molecules, thus improving salinity tolerance.

Three foliar treatments of 25 mg L⁻¹ SeNPs at the 4-5 leaf stage with 2-week intervals improved cucumber growth (plant height and leaf area) under combined salinity and heat stress conditions (Shalaby et al. 2021). Abdi et al. (2023) sprayed physalis under a 200 mM NaCl salinity environment with combined Si and SeNPs at 50 mg L⁻¹. They found that Si and SeNPs modulated salinity stress by increasing shoot and fruit weight, despite the evident biochemical changes associated with stress, such as increased phenol levels and decreased sugar content (Abdi et al. 2023). Soil and foliar application of 41 nm bio-SeNPs at concentrations ranging from 5 to 80 mg L⁻¹ restored yield and fruit composition of date palm under saline stress, increasing fruit weight by 58.6% and 101.2%, chlorophyll content by 28.8-29.5%, RWC by 33.3%, and ascorbic acid by 90.5% (El-Tarabily, AbuQamar 2025).

4.2. Drought

In drought conditions, SeNPs increased tomato leaf biomass and the content of carotenoids, phenols, and tocopherols, while also reducing hydrogen peroxide (H₂O₂), malondialdehyde (MDA), glutathione (GSH), and oxidized glutathione (GSSG). This indicates that priming tomato seeds with up to 100 mg L⁻¹ SeNPs resulted in a more efficient stress-mitigation response (Ishtiaq et al. 2023). A similar reaction of drought-stressed tomato plants was reported by Neysanian et al. (2024), who performed seven foliar sprayings at one-week intervals with 4 mg L⁻¹ SeNPs. They observed a similar decline in ROS content and an elevation of antioxidants in fruit, as Ishtiaq et al. (2023) found in leaves. A study by Zahedi et al. (2020) showed that spraying 100 mg L⁻¹ SeNPs three times during the cultivation of strawberries under drought conditions improved fruit quality and enhanced plant growth thanks to increased photosynthetic activity, chlorophyll fluorescence, water-use

efficiency, and the upregulation of catalase, peroxidase, and superoxide dismutase. Three foliar sprayings with Se/SiO₂NPs increased drought tolerance in strawberry by enhancing the activity of antioxidant enzymes, including catalase (CAT), ascorbate peroxidase (APX), guaiacol peroxidase (GPX), and superoxide dismutase (SOD). Additionally, lipid peroxidation and hydrogen peroxide (H₂O₂) content decreased. 100 mg L⁻¹ Se/SiO₂NPs improved fruit quality and nutritional value by increasing anthocyanin, total phenolic compounds (TPC), vitamin C, and antioxidant activity (DPPH) (Zahedi et al. 2020). In a similar experiment, three foliar applications of 100 mg L⁻¹ SeNPs in strawberry under water stress promoted plant growth, enhanced photosynthesis and water use efficiency, and restored fruit quality (Liu et al., 2024a).

Three foliar SeNPs spraying on pomegranate trees under drought conditions increased the yield, weight, and diameter of fruit, while also improving fruit composition by elevating phenols, osmolytes, and antioxidant enzymes levels (Zahedi et al. 2021). In another study, mango trees under drought conditions were sprayed three times with SeNPs, which resulted in higher yield, fruit weight, and size, as well as a decrease in fruit drop percentage. With increasing Se concentration, the NPs treatments improved fruit firmness, Total Soluble Solids (TSS), TSS-Acidity ratio, vitamin C, and sugar content. Se also reduced fruit acidity and increased leaf total chlorophyll content, leaf area, and the N, P, and K content in leaves, as well as shoot length and thickness (Almutairi et al. 2023).

4.3. Heavy metal and fungicide contamination

SeNPs were also found to be effective against the negative effects caused in plants by heavy metals. Li et al. (2022) discovered that SeNPs sprayed on soil at doses of up to 20 mg L⁻¹ helped pepper plants resist cadmium-related stress by increasing the synthesis of amino acids and stress-related signaling volatile organic compounds (VOCs). Similar results were reported by Liu et al. (2022a), where SeNPs restored fruit quality and composition harmed by the application of a fungicide containing penthiopyrad by mitigating negative changes in VOCs. The phytotoxic effect of penthiopyrad was also mitigated in tomato plants sprayed with 1 mg L⁻¹ SeNPs, which increased fresh weight and diameter and improved fruit flavor by elevating total phenols, flavonoids, and lycopene by 18.0%, 14.5%, and 9.92%, respectively (Liu et al., 2024b).

These results collectively reinforced the theory that SeNPs, when applied at proper species-specific concentrations, are capable of eliciting

abiotic stress responses in plants without critically impacting key functions. Instead, they enhance physiological parameters such as photosynthesis, growth, and yield, and activate biochemical machinery related to stress-resilience or hypersensitivity by boosting antioxidant enzyme activity and accumulating protective metabolites. This dual mechanism can be compared to the stress priming method, but unlike traditional priming, SeNPs can serve as a versatile tool to address several types of abiotic stress and their combined and cumulative effect.

5. SeNPs biofortification and fruit crop diseases

In addition to enhancing plant tolerance to abiotic stress, SeNPs have demonstrated antipathogenic properties, significantly improving plant resistance to fungal infections and nematodes (Fig. 3, Supplementary material Table S3).

5.1. Fungal and bacterial infections

Tomato plants sprayed with 20 mg L⁻¹ SeNPs five times every two weeks starting from the 11th day after transplanting reduced the severity of early blight (*Alternaria Solani*), increased chlorophyll levels, and enhanced the activity of antioxidant enzymes in leaves. Additionally, they showed increased vitamin C and glutathione content, and, similarly to what was reported above, enhanced flavonoid and phenol content in the fruit (Quiterio-Gutiérrez et al. 2019). Two post-inoculum sprayings with SeNPs at 100 mg L⁻¹ also reduced the incidence of leaf blight (*Alternaria alternata*) by 37% (El-Gazzar and Ismail 2020). Priming tomato seeds with 100 mg L⁻¹ SeNPs increased seed germination rates and fruit weight, and also upregulated enzymatic activity under late blight (*Phytophthora infestans*) conditions (Joshi et al. 2021). Helmy et al. (2023) primed tomato seedlings with 150 mg L⁻¹ SeNPs and transplanted them into soil contaminated with Fusarium wilt (*Fusarium oxysporum*). This treatment resulted in increased fruit weight, yield, plant height, and biomass, as well as a reduction in disease severity by up to 41.5%. Submerging harvested fruit in a SeNPs solution (concentration not reported) increased carotenoid content, reduced acidity, lowered the incidence of *Fusarium oxysporum* and *F. moniliforme*, decreased weight loss, and thus improved the shelf-life of tomatoes (Manaa et al., 2023).

Limited data are available about the effects of SeNPs on bacterial

pathogens. Coating harvested tomatoes with cassava starch-based films containing 1% and 2% Bio-SeNPs showed antimicrobial effect against *Listeria spp.*, *Salmonella spp.*, *E. coli* (Nogueira et al. 2024). Priming tomato seeds with SeNPs at 10, 20 and 30 mg L⁻¹ inhibited both fungal (*Fusarium oxysporum*, *Aspergillus niger*) and bacterial infections (*Pseudomonas syringae*, *Xanthomonas campestris*) (Maqbool et al. 2025). Assad et al. (2025) reported that 18.76 nm SeNPs applied to soil at 1, 2, and 3 mg kg⁻¹ were effective against *Xanthomonas spp.* on tomato and lime, also increasing plant growth and chlorophyll content.

Apart from tomato, other fruit crops also showed an improvement of shelf life and elevated resistance to fungal diseases when treated with SeNPs during postharvest. Coating grapes with biofilm containing up to 150 mg L⁻¹ SeNPs inhibited sporogenesis of *Fusarium oxysporum* and *Sclerospora graminicola* (Hadimani et al. 2023). Treating strawberries with SeNPs-containing gel prolonged their shelf-life under grey mold (*Botrytis cinerea*) infection (Liu et al. 2022b). Coating harvested persimmons with a chitosan-based gel containing SeNPs resulted in increased fruit firmness and reduced the severity and incidence of black rot (*Alternaria alternata*) (Salem et al. 2022a). A similar SeNPs gel coating treatment was effective in protecting harvested oranges from green mold infection (*Penicillium digitatum*) (Salem et al. 2022b).

5.2. Nematodes

SeNPs were found to be effective against nematodes. Udalova et al. (2018) reported that a double application - soaking tomato seeds followed by foliar spraying with up to 0.68 mg L⁻¹ SeNPs - accelerated seed germination, stimulated plant growth, and reduced the number and size of root-knot nematode (*Meloidogyne incognita*) galls. This effect was attributed to enhanced activity of proteinase inhibitors through the modulation of PR 6 gene expression, which serves as a marker of systemic resistance to infection. Similar results were observed by Nikam et al. (2023), who reported a reduction of *Meloidogyne sp.* incidence due to induced protease inhibitors in roots and leaves after priming seeds and spraying plants 8 times with 10 mg L⁻¹ SeNPs.

Foliar spraying of tomatoes with up to 10 mg L⁻¹ SeNPs also reduced *Meloidogyne incognita* gall number by 91%, as well as increased chlorophyll a and b, carotenoid content, and upregulated catalase and peroxidase (Daoush et al. 2023).

It remains unclear whether these effects are due to the direct impact

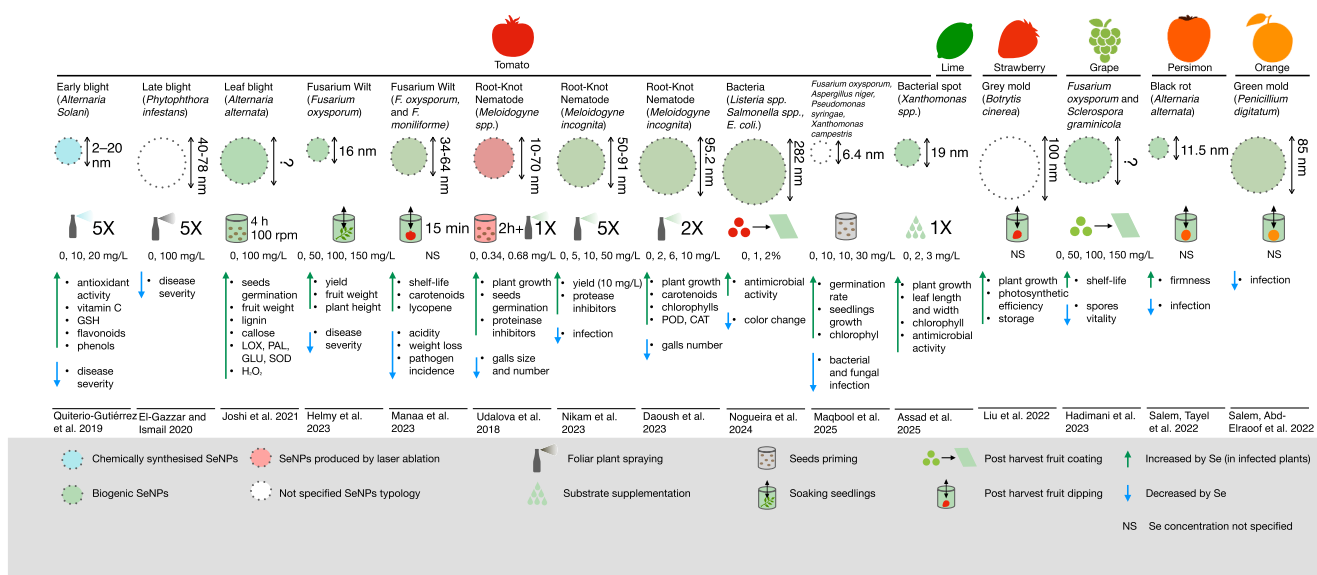


Fig. 3. Effects of SeNPs type and application method on Se content, yield, and fruit characteristics in crops infected by various pathogens or nematodes. The applied Se concentration is expressed in mg/L, and the Se content in fruit tissue was not reported in all cited studies. The symbols color corresponds to the type of NPs while symbols shape represents the treatment method.

of SeNPs on pathogens or if there is an intermediate step, possibly a hypersensitivity reaction activated by selenium in the plant. For example, [Tran et al. \(2023\)](#) observed that 300 mg L⁻¹ Nano Se coating inhibited *Neopestalotiopsis rosae* and *Fusarium oxysporum* under single-species strawberry culture conditions. [Liu et al. \(2022b\)](#) reported that SeNPs reduced *Botrytis cinerea* colony area in *in vitro* conditions. Similarly, [Salem et al. \(2022a\)](#) observed a reduction in the radial growth of *Alternaria alternata* *in vitro*, while also reporting a positive effect of SeNPs on the antipathogenic activity in persimmon fruit. [Salem et al. \(2022b\)](#) showed that direct treatment of *Penicillium digitatum* mycelia with SeNPs resulted in lysis and deformations of hyphae. Further *in-vitro* experiments examining the direct interaction between microbes and SeNPs are necessary to better understand this complex issue.

6. Critical comments and conclusions

6.1. Experimental design: Selenium salts or nanoparticles?

Often, the effect of SeNPs is compared with the behaviour of untreated plants/fruits, rather than with the corresponding concentration of sodium selenate or other form of Se. This raises the question of how accurate it is to report the observed results and claim them to be caused by the nanoform of Se rather than by selenium itself. From this observation, we may conclude that for certain parameters, Se form does not cause the difference, but only the amount of Se delivered. A large portion of papers did not quantify or report the results of Se analysis in the investigated material. Without such data, it becomes difficult to draw conclusions about the strength of Se treatment in general, or the effects of its specific forms.

Recent literature reports Se nanoparticles as a potential alternative to sodium selenate for crop biofortification. The efficiency of SeNPs in delivering Se in plant organs ([Shiriaev et al. 2022](#)), along with the associated regulatory and physiological consequences, is then compared with the corresponding effects of sodium selenate ([El-Badri et al. 2022](#)). This practice may give the impression that SeNPs represent a single chemo-physical form of Se. Observed studies reported NP sizes ranging from 2 to 282 nm; however, 17% of the selected studies (7 papers) did not report the size of NPs. Additionally, 55% of the papers (22 papers) do not provide any information on the NPs typology or NPs synthesis method. This lack of data makes it challenging to develop a solid model explaining how the characteristics of SeNPs and their nature affect fruit crops.

6.2. Unclear indirect dynamics between applied dose and the effects: A double-edged sword

Based on multiple studies, we may assume that there is no linear pattern between Se accumulation in tissues from SeNPs and the strength of the physiological or biochemical consequences. Often, weaker treatments result in stronger effects. For example, [Li et al. \(2022\)](#) reported that SeNPs treatment affected genes in the phenylpropane-branched fatty acid pathway (BCAT, Fat, AT3, HCT, and Kas) when applied at a concentration of 5 mg L⁻¹. However, they also applied lower and higher doses (1 and 20 mg L⁻¹) that did not produce such significant results.

Another challenge is ensuring that the reported results are indeed derived from Se accumulated by tissues. Among the 40 studies reporting treatments of fruit crops with Se nanoparticles, only 12.5% (5 papers) reported Se content in treated plants. Interestingly, in some cases ([Zahedi et al., 2021](#); [Sariñana-Navarrete et al., 2023](#)), the trend of biochemical changes is negatively, or non-linearly ([Reyes-Pérez et al. 2025](#)) correlated with Se level in the treatment and is not proportional to the internal Se level. This supports the hypothesis that the mechanism of SeNPs' action in plants is a double-edged sword: it stimulates the stress response itself, thus activating stress-resilience mechanisms that allow plants to better withstand various abiotic and biotic stresses.

6.3. Number of treatments and SeNPs typology

The number of treatments does not seem to have a direct link with the efficacy of Se accumulation. However, 50% of the studies (20 papers) report multiple treatments, ranging from 2 to 7. It is also difficult to compare different types of SeNPs (biogenic vs chemical) and their efficacy on Se uptake, as well as the secondary impacts on plant physiology and biochemistry, due to the lack of details in the reported protocols. Only 3 of the studies report the use of chemically produced SeNPs. Most papers that report these details provide data related to biogenic SeNPs, accumulating more evidence on this SeNPs typology and reinforcing the hypothesis that biogenic SeNPs are more applicable in fruit biofortification than the chemical ones.

6.4. Semantics

Lastly, the diversity of semantics used to define NPs creates difficulty in literature search and analysis. Terms such as nano-selenium, selenium nanoparticles, and selenium liposomes are just a few examples. The same issue applies to acronyms: SeNPs ([Shiriaev et al. 2022](#); [Ishtiaq et al. 2023](#); [Nikam et al. 2023](#)), Se-NPs ([Zahedi et al. 2019a](#); [Liu et al. 2022a](#)), BioSeNPs ([Daoush et al. 2023](#)), nSe ([Sariñana-Navarrete et al. 2023](#)), N-Se ([Zahedi et al. 2019b](#)), Nano Se ([Tran et al. 2023](#)), NPSe ([Montaño-Herrera et al. 2022](#)). In some cases, the same group of authors uses different acronyms and terms in their reciprocally cited papers, such as nano-Se ([Li et al. 2022](#)) referencing a description of nanoparticles from a source where the term SeNPs is used ([Li et al. 2020](#)). We suggest adopting a consistent terminology to define NPs, and based on our review, Se Nanoparticles (SeNPs) is the most commonly used term.

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CRediT authorship contribution statement

Anton Shiriaev: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stefano Brizzolara:** Writing – review & editing, Validation. **Fernando Malorgio:** Writing – review & editing, Validation. **Pietro Tonutti:** Writing – review & editing, Validation, Supervision, Methodology, Data curation. **Beatrice Pezzarossa:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Data availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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