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Nano-Selenium and its Interaction with other Nano-Nutrients in Soil under Stressful Plants: A Mini-Review

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THE MASSIVE application of nanoparticles in many sectors including medicine, agriculture and industry caused their inevitable release into different environmental compartments particularly groundwater and soil. The fate and behavior of these nanoparticles in soil and groundwater and their effects on soil biosystem remain largely unaddressed. Nano-selenium (Se-NPs) has intensive applications nowadays in different agroecosystems, but several studies, which highlight this behavior in plants and soils were carried out in individual case studies. In this concern, the interaction of nano-selenium with different nano-nutrients in soils and their uptake by cultivated plants still need urgent investigations. Based on the interaction is a common feature in the nature, there are still many unanswered questions regarding the interaction of Se-NPs with other nano-nutrients in soil for example: are these reactions synergistic or antagonistic? What are the factors controlling the bioavailability of nano-Se in soil in presence of other nano-nutrients? What is the expected role of stressful plants in orientation of this interaction among nano-nutrients?

Keywords: Biotic stress, Nano-silica, Plant pathogens, Nano-copper oxide, Nano-zinc oxide

Introduction

Plants can grow under different conditions including natural and stressful ones, but the productivity of cultivated plants definitely will be decreased due these stressors. Several studies have been published on the understanding response of these stressful plants. These studies have increased our knowledge in understanding the plethora of biochemical, physiological, morphological, cellular and molecular responses under stressful plants (Saini et al. 2021). These stressors may include the abiotic stresses like salinity, drought, flooding, pollution, and heat stress; the biotic stress,

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which result from the pathogens (Lassalle 2021). Under stressful conditions, many mechanisms or approaches take part to mitigate plant stress *via* endogenous agents such as phytohormones including cytokinin, gibberellin, ethylene, abscisic acid, brassinosteroids, salicylic acid and jasmonates (Saini et al. 2021) and/or exogenous factors like applied Se/nano-Se (Shalaby et al. 2021), Si/nano-Si (Akhtar et al. 2021), nano-TiO_2 (Ogunkunle et al. 2020; Shah et al. 2021), nano-ZnO (Ahmed et al. 2021a), nano-CuO (Jośko et al. 2021), nano-iron/relatives (Zhang et al. 2021), and nano-organic fertilizer (Ahanger et al. 2021). As common studies, several investigations on individual nanoparticles on stressful plants have been published, but few studies were reported on combined nanoparticles (e.g., Ahmed et al. 2021a; Jośko et al. 2021; Badawy et al. 2021).

Nano-selenium (i.e., nano-Se or Se-NPs) has unique properties like high bioavailability, low toxicity, high biological activity, high particle dispersion, and large surface area (Kumar and Prasad 2021). Thus, these nano-particles are widely in many sectors like medicine, e.g., drug delivery systems, medical diagnostics, antimicrobial agent, an antioxidant, anticancer agent, dietary supplement, and antidiabetic agent (Li and Xu 2020; He et al. 2021). In the agricultural sector, nano-Se has many beneficial effects on plant growth especially as nano-fertilizer (Gudkov et al. 2020), plant anti-stress (Shalaby et al. 2021), and nano-biofortification (El-Ramady et al. 2020, 2021a, b).

Therefore, this mini-review is an attempt to provide insight on the following themes (i) the distinguished role of nano-Se for decreasing plant stress, (ii) what is the fate and behavior of nano-nutrients in soils, and (iii) what is the expected interaction among nano-Se and other nano-nutrients? This is a call from the EBSS Editorial-board for more publications concerning this interaction among nano-nutrients in soil.

Nano-Se for stressful plants

A stress could be defined as "*the consequence of adverse effects of an external factor called stressor – or stress factor – on plant functions growth, and development*". Cultivated crops face great challenges especially under environmental stresses, which decrease their productivity (Lassalle 2021). Environmental stressors include both abiotic stress (i.e., physical or chemical factors like salinity, drought, flooding, pollution) and biotic stress, which resulted from organisms like plants, pathogens, insects (Othman et al. 2014; Lassalle 2021). Crop productivity has become limited under stressful conditions, which result from both the natural and anthropogenic origins (Lassalle et al. 2020). Many amendments have been used to mitigate biotic and abiotic stresses on cultivated plants particularly nanoparticles, e.g., Ag-NPs (Alabdallah and Hasan 2021), nano-TiO_2 (Ogunkunle et al. 2020) or nano-nutrients like nano-Se (Seliem et al. 2020; Qi et al. 2021), nano-silica (Lian et al. 2021), nano-CuO (Cota-Ruiz et al. 2020; Noman et al. 2020), nano-MgO (Ghassemi-Golezani et al. 2021), and nano-iron (Moradbeygi et al. 2020; Sreelakshmi et al. 2021).

Concerning nano-Se and its role to support the stressful plants, many studies confirmed this role, which is represented in the following investigations:

1- Enhancing peanuts plants (*Arachis hypogaea* L.) due to exogenous foliar application of nano-Se by activating antioxidant system under deficiency of nutrients in sandy soils (Hussein et al. 2019a).

2- Promoting the yield of pomegranate (*Punica granatum* L.) and its quality under arid zone (Zahedi et al. 2019b).

3- Alleviating Cd-toxicity in rice (*Oryza sativa* L.), Moldavian balm (*Dracocephalum moldavica* L.), and oilseed rape (*Brassica napus* L.) by modulating photosynthesis parameters and activities of antioxidant enzymes (Hussain et al. 2020; Azimi et al. 2021; Qi et al. 2021; Wang et al. 2021a).

4- Mitigating chilling stress on sugarcane (*Saccharum officinarum* L.) photosynthesis (Elsheery et al. 2020).

5- Protecting lettuce plants (*Lactuca sativa* L.) and strawberry (*Fragaria × ananassa* Duch) from salinity stress (Zahedi et al. 2019a; Soleymanzadeh et al. 2020).

6- Reducing the negative impacts of heat stress on *Chrysanthemum morifolium* Ramat by enhancing antioxidant enzyme activities particularly peroxidase and catalase at 150 mg nano-Se L^{-1}; decreasing electrolyte leakage and polyphenol oxidase at 200 mg nano-Se L^{-1} (Seliem et al. 2020).

7- Boosting the growth of cucumber (*Cucumis sativus* L.) and its productivity under soil salinity under heat stress by regulating the osmotic balance and controlling stomatal opening through the high K^+ content in cucumber leaves, which might support stressful cultivated plants (Shalaby et al. 2021).

8- Alleviating the salinity stress on bitter melon (Momordica charantia) plants by increasing proline, K+ and relative water content, the activity of antioxidant enzymes, and decreasing content of oxidants MDA and H2O2 (Sheikhalipour et al. 2021).

9- Enhancing the quantity and quality of grains of wheat (Triticum aestivum L.) by 5–40%, under drought and heat stress as well as enhancing their tolerance to wheat crown and root rot diseases (El-Saadony et al. 2021a).

Many studies reported about the protective role of nanoparticles against many plant pathogens (i.e., bacteria, fungi, actinomycetes and nematode) like Ag-NPs (Gogoi et al. 2020; Javed et al. 2020; Paul and Roychoudhury 2021), SiO_2-NPs (Parveen and Siddiqui 2021), CuO-NPs (Ahmad et al. 2020; Mehta et al. 2020; Sathiyabama et al. 2020), La_2O_3-NPs (Adeel et al. 2021b), ZnO-NPs (Sharma et al. 2020; Khan and Siddiqui 2021), and carbon-based nanomaterials (Adeel et al. 2021a). On the other hand, few studies caried out on the role of nano-Se in supporting the cultivated plants under biotic stress like El-Saadony et al. (2021a), who investigated the wheat crown and root rot diseases induced by *Fusarium* spp. (i.e., *Fusarium culmorum*; *Fusarium graminearum*). Some studies also were reported on using of Se-NPs in controlling tomato leaf blight caused by *Alternaria alternata* under greenhouse conditions (El-Gazzar and Ismail 2020), and against tomato late blight disease (Joshi et al. 2021). More studies on stressful plants under biotic stress are needed including different phyto-diseases (e.g., leaf and root wilt, stem and leaf bright, leaf spot, stem canker, and soft rot). Some experiments were carried out in the Lab on nano-Se including *Alternaria solani* (Early blight) in tomato and potato (**Fig. 1**), *Rhizoctonia solani* (**Fig. 2**), and *Trichoderma* (**Figs. 3 and 4**).

Nano-nutrients in soils

Day by day, huge amounts of applied nanomaterials and/or nanoparticles are being used in different agroecosystems. The environmental content of nano-materials was predicted in soils to be within the ranged of 10^{-7} to 10^{2} mg kg^{-1}, and in landfills is thought to be about 10^{-3} to 10^{3} mg kg^{-1} (Adeel et al. 2021b). Several transformations could happen once nanoparticles release into soil, which may include adsorption, dissolution, sulphidation, aggregation and redox reactions (Jośko et al. 2021). This release and dynamics of NPs in soil may depend mainly on characterization of NPs and soil, and may include soil pH, clay content, soil organic matter, cation exchange capacity and the rhizosphere characterization (Gao et al. 2017, 2019; Jośko et al. 2020). The fate and behavior of nano-nutrients

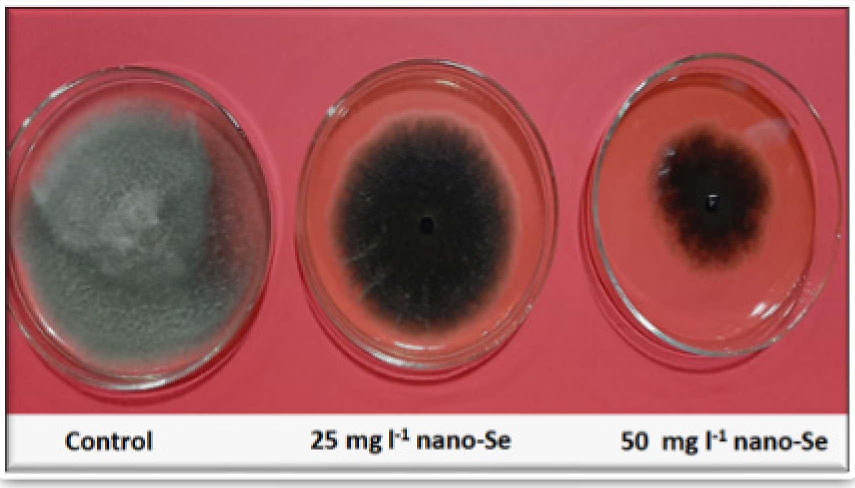

Fig. 1: Effect of nano-selenium on Alternaria solani (Early blight) in tomato and potato was investigated on PDA media using 0, 25, and 50 mg l^{-1} nano-Se. These Petri dishes were infected by Alternaria solani and after 9 days from complete the growth in control petri dish, the reduction (inhibition rete) was calculated to be 25 and 75% for the 25 and 50 mg l^{-1} nano-Se, respectively

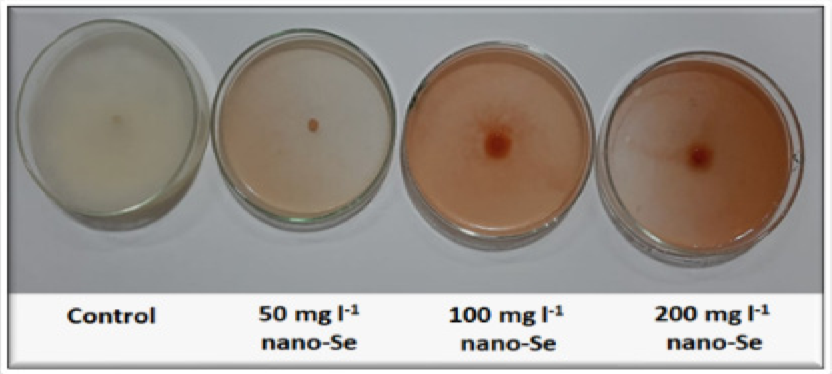

Fig. 2: Effect of nano-selenium on Rhizoctonia solani (as root rot or damping off or stem rot) was investigated on PDA media using 0, 50, 100 and 200 mg l-1 nano-Se. These Petri dishes were infected by Rhizoctonia solani and after 4 days from complete the growth in control petri dish, the reduction (inhibition rete) was calculated to be 50, 50 and 75% for the 50, 100 and 200 mg l-1 nano-Se, respectively

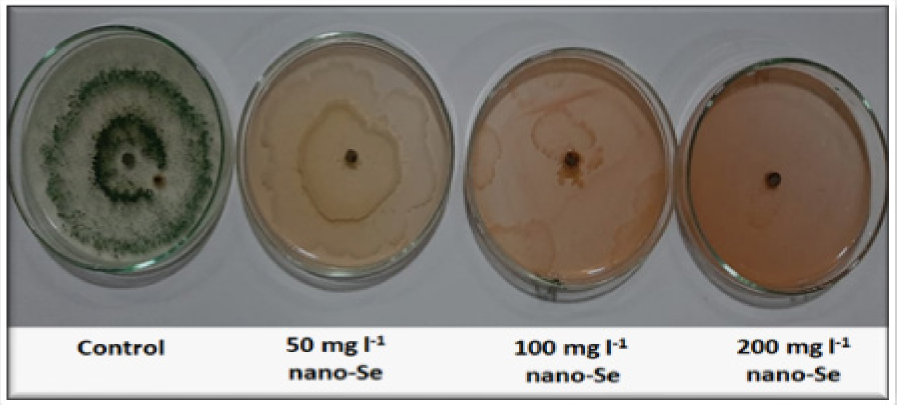

Fig. 3: Effect of nano-Se on Trichoderma spp. was very strange, where it was noticed that nano-Se changed the way of growing Trichoderma in the media and changed its behavior without inhibiting its growth. This may explain the reason of increasing the effectiveness of Trichoderma, but this needs further study for confirming

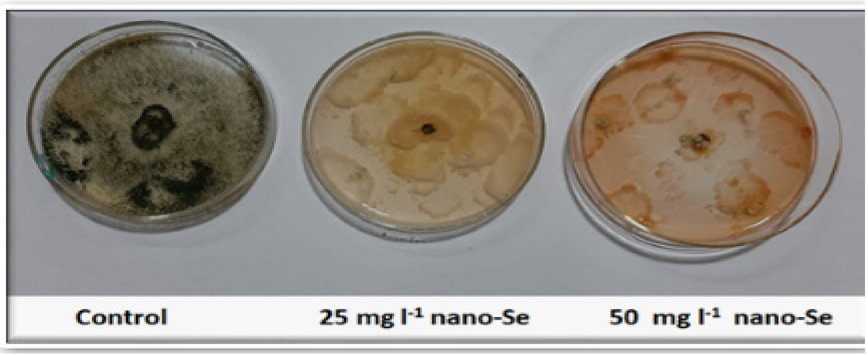

Fig. 4: Effect of nano-Se on the growth of Trichoderma spp. After 30 days from nano-Se treatment, Trichoderma changed the way of growing in the media, but changed its behavior without inhibiting its growth. This may help in increasing the effectiveness of Trichoderma.

or NPs in soil could be followed through three stations (*i*) nano-nutrients-soil interactions, (*ii*) nano-nutrients-rhizosphere interaction and (*iii*) nano-nutrients-plant interaction. Concerning the first station, soil environment can control the mobility of NPs, bioavailability and their toxicity in soil, which determine fate and sorption of nano-nutrients and subsequent impact on plants (Gao et al. 2018). Regarding nanoparticle-rhizosphere interaction, it is controlling by soil type (sandy, clayey, loamy) and time of exposure to NPs. In rhizosphere, different metabolites secreted (exudates) by plants and soil organisms and these exudates can modulate the fate of nano-nutrients (Gao et al. 2018). These root exudates are abundant mixtures in rhizosphere that control the behavior of NPs including organic acids, amino acids, sugars, and phenolics as low-molecular weight compounds and high-molecular weight compounds like mucilage (Gao et al. 2018; Wang et al. 2020). The third station (nano-nutrients-plant interaction), the phytotoxicity of nano-nutrients is governed by three factors including (1) plant type, species, and its growth stage, (2) nano-nutrients including size of NPs, concentration, and its aggregation and (3) growth media or experimental conditions including time, temperature, and method of exposure (Ahmed et al. 2021b).

Some distinguished attempts were already achieved on the fate and behavior of nano-nutrients or nanoparticles in soils and in some cases under cultivated plants, which could present in the following section:

1- The behavior of NPs and their bioavailability in soil under driven factors by rhizosphere processes, which include root exudates, the activities of soil microbes and earthworm, signal transduction as well as nano-nutrients absorption and their transport (Wang et al. 2020c).

2- Many kinds of nanoparticles have been discussed in the soil-plant environment including the interactions, assessing of their applications, fate and toxicity (Shrivastava et al. 2019; Rajput et al. 2020; Ameen et al. 2021; Rizwan et al. 2021) like iron oxide-NPs (Kamran et al. 2020), copper-based NPs (Bakshi and Kumar 2021), silver-NPs (Courtois et al. 2021), TiO_2-NPs (Chavan et al. 2020), CeO_2-NPs (Prakash et al. 2021), gold-NPs (Malejko et al. 2021), and nano-silica (Lian et al. 2021).

3- The expected interaction of nanoparticles with soil were reported by Ogunkunle et al. (2021). They discussed different NPs-sources and their transport into the soil with focus on NPs-characterization including their shape, surface chemistry, size, and water solubility, which may control the fate of NPs in soil and their various processes.

4- The release and behavior of nanoparticles in soils may follow one of the three following pathways for the interaction of NPs and soil components like (*i*) soil enzymes (de Oca-Vásquez et al. 2020; Mishra et al. 2021), (*ii*) soil properties particularly soil organic matter (Simonin et al. 2021), and (*iii*) soil macro-/microbial communities (Ameen et al. 2021; Macůrkova et al. 2021).

Concerning the efficacy of Se-NPs in soil, there are many multipurpose action and additional problems involved in the soil application of Se-NPs, which is related to content of soil organic matter (SOM) and its stimulation by the humic substance (HS) supplied simultaneously with Se and other nanoparticles. With respect that HS, Se-NPs, and SOM functioning in the soil are linked to the degradation of organic matter, which is mainly controlled by soil microbial activities and linked to the soil fertility (Gudkov et al. 2020). The proper Se-NPs functioning in soil is controlling by soil tillage, ploughing and other soil cultivation procedures, which may be linked to formation of soil aggregates system. Soil moisture content also is an important factor controlling the functions of Se-NPs, HS, poly-microbial biofilms and the plant growth. The high soil water content (flooding) may cause a problem in leaching the nanoparticles and other soil matters (Gudkov et al. 2020). The profile distribution of natural NPs in paddy soils may affect by long-term rice cultivation (Huang et al. 2021).

Some published studies focused on responses of different cultivated crops to many different nanoparticles like applied NPs of Al_2O_3, CuO, TiO_2, ZnO to cucumber plants cultivated on sandy-clay-loam field soil (Ahmed et al. 2021c). Many metal-oxide NPs are transformed by environmental factors such as CuO-NPs, which could be degraded into copper sulfate hydroxides and then release Cu^{2+} that increases the bioavailability of Cu in soil and its bio-uptake by cultivated plants (Servin et al. 2017). Concerning the uptake of nano-Se, cultivated plants can take up the Se-NPs, which can influx into roots as a "*passive diffusion process*" and the uptake rate of nano-Se (chemical and biological forms) is lower than for the selenite form (Hu et al. 2018). The chemical nano-Se could easily uptake by plant roots more than the biological one especially when the nanoparticles are below 50 nm in size. Few nanoparticles indicate that Se could be transported from plant roots into shoots, and then they will rapidly assimilate into selenite and organic forms in roots and shoots. The uptake of Bio-Se-NPs could be inhibited by aquaporins inhibiter in a higher rate compared to chemical Se-NPs in 93.4 and 92.5%, respectively (Hu et al. 2018). In general, the uptake rate of selenite and selenate was approximately equal, and both exhibited higher uptake rate than nano-Se, which was estimated, in case of selenite, by 2.5-fold higher than nano-Se (Hu et al. 2018). Concerning the transformation of nano-Se in roots, it is found that selenite was rapidly assimilated in wheat roots into organic forms (e.g., SeMet), whereas the nano-Se appeared stable in the solution and did not oxidize to selenite (Hu et al. 2018). The uptake of Se-NPs rice roots was confirmed; then they can transport successfully into the aerial parts and the dominant Se-species was SeMet under different Se-NPs treatment (Wang et al. 2020b). Selenium is characterized by its ability to be lost via volatilization into the atmosphere such as H_2Se, DMSe, DMDSe, DMSeS, and $DMSeO_2$, where Se-species "DMSe" is the main dominant volatile Se species (Ye et al. 2021). The great role of microorganisms in Se is to biosynthesize the nano-Se (11 – 700 nm in diameter), whereas the biosynthesized organic form by fungi ranges from 17 to 150 nm (Wang et al. 2022). Red elemental nano-Se spheres in water may produce H_2Se and H_2SeO_3 in small amount according to the following equation $3Se + 3H_2O \leftrightarrow 2H_2Se + H_2SeO_3$. Afterwards, H_2Se and H_2SeO_3 may react together and precipitate forming crystals when the solution (El-Ramady et al. 2015).

Nano-Se and its interaction with other nano-nutrients

Several studies have been published about the individual impacts of nanoparticles of different nutrients on cultivated crops like nano-Se (Shalaby et al. 2021), nano-silica (Mathur and Roy 2020; Lian et al. 2021), nano-Cuo (Li et al. 2021), nano-Fe_2O_3 (Zhang et al. 2021), and nano-ZnO (Keerthana et al. 2021), but few studies focused on the combined impact of two or more nano-nutrients (**Table 1**). The co-existence of different engineered nano-nutrients in the agro-environment is an emerging issue remaining poorly investigated (Jośko et al. 2021). **Table 2** presents some published studies to be compared nano-Se and its interaction with some other nano-nutrients.

Many of these nano-nutrients applied to mitigate the plant stressful conditions like drought (Zahedi et al. 2020), heavy metals stress (Hussain et al. 2020; Wang et al. 2020a), and soil salinity (Badawy et al. 2021). Concerning the heavy metals pollution, foliar application of the combined nano-Se and nano-Si has shown success in decreasing the accumulation of Cd and Pb metals in rice grains, hence improved the rice grain quality and Se-biofortification (Hussain et al. 2020). Some mixtures of nano-nutrients like nano-ZnO and nano-CuO caused a reduction in the inhibition of root elongation of cress, cucumber, flax, and wheat comparing with single exposure to these particles (Jośko et al. 2017). On the other hand, some studies reported the opposite trend like a higher reduction in spinach biomass irrigated with mixtures of nano-CuO and nano-ZnO than individual treatments (Singh and Kumar 2020). The bioactivity of these nano-nutrients may be attributed to nature of these nano-nutrients (García-Gomez et al. 2017). In other study, the mixtures of nano-CuO and nano-La_2O_3 decreased the accumulation of Cu in zucchini plant tissues than single exposure to its NPs (Pagano et al. 2017). So, several studies demonstrated the changes in the nutritional profile of many plants exposed to different-NPs (Cota-Ruiz et al. 2020; Sharifan et al. 2020). Therefore, an urgent question arises then about how the mineral composition of plants will be affected by co-existing these nano-nutrients (Jośko et al. 2021).

Combined application of nano-Se and nano-SiO_2 at both 50 and 100 mg L^{-1} improved the yield and fruit quality of strawberry plants compared to the control which was grown under normal and drought stress conditions, which included normal irrigation at 100% Field Capacity (FC), moderate stress at 60% FC, and severe stress at 25% FC. The highest dose of applied nano-Se and nano-SiO_2 (100 mg L^{-1}) preserved more of their photosynthetic pigments compared with other treated plants and presented higher levels of key osmolytes such as carbohydrate and proline. Applied nano-Se/SiO_2 improved strawberry fruit quality and nutritional value (total phenolic compounds, anthocyanin, vitamin C and antioxidant activity) under drought stress (Zahedi

TABLE 1: The most important nano-nutrients already used in crop production and some details concerning cultivated crop, and some individual and combined published studies

Nano-nutrient alone or and its coexistence nano-nutrient	Cultivated crop and its scientific name	References
Some published studies on individual nano-nutrients		
Nano-Se	Cucumber (*Cucumis sativus* L.)	Shalaby et al. (2021)
	Chicory (*Cichorium intybus* L.)	Abedi et al. (2021)
	Wheat (*Triticum aestivum* L.)	El-Saadony et al. (2021a)
	Lemon balm (*Melissa officinalis* L.)	Ghasemian et al. (2021)
	Common bean (*Phaseolus vulgaris*)	Rady et al. (2021)
	Rice (*Oryza sativa* L)	Wang et al. (2020b)
	Groundnut (*Arachis hypogaea* L.)	Hussein et al. (2019a, b)
	Tomato (*Solanum lycopersicum* L.)	Neysanian et al. (2020)
	Tomato (*Solanum lycopersicum* L.)	Morales-Espinoza et al. (2019)
Nano-Cu or Cuo	Rape (*Brassica napus* L.)	Li et al. (2021)
	Alfalfa (*Medicago sativa* L.)	Cota-Ruiz et al. (2020)
	Maize (*Zea mays* L.)	Pu et al. (2019)
	Bell pepper (*Capsicum annuum*)	Rawat et al. (2019)
Nano-Fe and relatives	Rice (*Oryza sativa* L.)	Zhang et al. (2021)
	Fever nut (*Caesalpinia bonducella*)	Khalid et al. (2021)
	Foxtail millet (*Setaria italica*)	Sreelakshmi et al. (2021)
nZVI	Rice (*Oryza sativa* L.)	Guha et al. (2020)
	Sweet basil (*Ocimum basilicum* L.)	Tavallali et al. (2020)
Nano-MgO	Fever nut (*Caesalpinia bonducella*)	Khalid et al. (2021)
	Cowpea (*Vigna unguiculata* L.)	Tauseef et al. (2021)
Nano-Si or silica	Wheat (*Triticum aestivum* L.)	Akhtar et al. (2021).
	Rice (*Oryza sativa* L.)	Banerjee et al. (2021)
	Common bean (*Phaseolus vulgaris*)	El-Saadony et al. (2021b)
	Lemon balm (*Melissa officinalis* L.)	Hatami et al. (2021)
	Maize (*Zea mays* L.)	Kumaraswamy et al. (2021)
	Lettuce (*Lactuca sativa* L.)	Lian et al. (2021)
Nano-Zn or ZnO	Okra (*Abelmoschus esculentus* L.)	Keerthana et al. (2021)
	Wheat (*Triticum aestivum* L.)	Rai-Kalal et al. (2021)
	Onion (*Allium cepa* L.)	Debnath et al. (2020)
	Rice (*Oryza sativa* L.)	Chutipaijit et al. (2018)
Some published studies on combined nano-nutrients		
Nano-CuO and nano-ZnO	Maize (*Zea mays* L.)	Ahmed et al. (2021a)
nano-CuO and nano-ZnO	Barley (*Hordeum vulgare* L.)	Jośko et al. (2021)
Nano-Se and nano-ZnO	Lemon balm (*Melissa officinalis* L.)	Babajani et al. (2019)
Nano-Se and Nano-Si	Rice (*Oryza sativa* L.)	Badawy et al. (2021)
Nano-Se and nano-copper	Tomato (*Solanum lycopersicum* L.)	Hernández-Hernández et al. (2019)
Nano-Se and nano-copper	Tomato (*Solanum lycopersicum* L.)	Quiterio-Gutiérrez et al. (2019)
Nano-Se and Nano-Si	Rice (*Oryza sativa* L.)	Hussain et al. (2020)
Nano-Se and Nano-silica	Strawberry (*Fragaria×ananassa* Duch.)	Zahedi et al. (2020)

Note: **nZVI**: nano-scale zero valent iron

TABLE 2: Some published case studies of the interaction of nano-Se and other nano-nutrients applied for cultivated plants

Cultivated plant and its scientific name	Nano-Se and its applied dose	Applied nano-nutrient and its details	Purpose of the study	Reference
Rice (*Oryza sativa* L.)	Chemical nano-Se (12.26 nm) at 5, 10 and 20 mg L^{-1}	Nano-silica (18.04 nm) at 5, 10 and 20 mg L^{-1}	Foliar applied of both NPs regarded the accumulation of Cd and Pb in rice grains	Hussain et al. (2020)
Rice (*Oryza sativa* L.)	Se-NPs at 4, 6, and 12 mg L^{-1} (75 nm)	Si-NPs at 15, 22, and 44 mg L^{-1} (6 and 7 nm)	Foliar applied Si and Se-NPs reduced Cd and Pb translocation to rice grains; mitigate oxidative damage	Wang et al. (2020a)
Strawberry (*Fragaria×ananassa* Duch.)	Chemical Se-NPs (10-45 nm) in combined with nano-silica	Spraying SiO_2-NPs (20-30 nm), SiO_2, Se, and nano-Se/SiO_2 at 50, 100 mg l^{-1}	Both nano-Se and nano-silica supported cultivated strawberry under drought stress	Zahedi et al. (2020)
Lemon balm (*Melissa officinalis*)	Chemical nano-Se at 10, and 50 mg l^{-1} (10-45 nm)	Nano-ZnO (10–30 nm) at 100, and 300 mg l^{-1}	Possible impacts of both nano-nutrients on growth, toxicity, and antioxidants in plants	Babajani et al. (2019)
Tomato (*Solanum lycopersicum* L.)	Chemical Se-NPs at 1, 10, 20 mg L^{-1} (2-20 nm)	Cu NPs at 10, 50, 250 mg L^{-1} (42 nm)	Combined nano-nutrients increased yield and fruit quality of tomato	Hernández-Hernández et al. (2019)
Tomato (*Solanum lycopersicum* L.)	Chemical Se-NPs at 10 and 20 mg L^{-1} (2–20 nm)	Cu-NPs at 10 and 50 mg L^{-1} (50 nm)	Applied nanoparticles increasing antioxidant capacity under early blight disease stress	Quiterio-Gutiérrez et al. (2019)

et al. 2020).

On the other hand, the diverse aspects of the interplay between different-NPs and cultivated plants are very important for discussing this interplay (Hu and Xianyu 2021). Therefore, several questions could be asked concerning the combined application of nano-nutrients and the expected interaction like: what will be happened when the nano-nutrients apply as binary mixtures? Is this mixture of anno-nutrients synergistic or antagonistic for plant growth? To what extent we can expect the interactions of combined exposure of nano-nutrients, which may include adsorption and/or competition between ionic and particulate metals as well as with biomolecules?

Conclusions

The rising wide-scale uses of Se-NPs for different applications in agriculture, industry, and environmental issues would undoubtedly lead to their dissemination in the agroecosystems (mainly groundwater and soil). Based on the environmental impacts of Se-NPs are speedily progressing in individual cases, some major understanding is needed on Se-NPs mechanism of their interactions with other nano-nutrients in different soil components and their subsequent impacts on plants and microorganisms. Several nanoparticles already were investigated for their fate, behavior and impacts on the soil-plant system, but the combined and multi-impacts nano-nutrients still need further investigations. These multi-interaction cases in soil might influence by the functioning of the soil nutrient cycles, soil microbial activity, different reactions in the rhizosphere, plant exudates, and soil properties. Concerning the bio-transformation of Se-NPs or their chemical complexes in soil, this important area still needs future investigations. The phytotoxicity of Se-NPs and its uptake might vary in different plant species and the structure of exposure media. Several open questions are still needed to be investigated such as what is the expected mechanism of nano-nutrients and their role in rhizosphere and their interactions in influencing Se-NPs plant uptake and translocation? What are the expected and different pathways of nano-Se interactions with other nano-nutrients in soil based on their individual properties?

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The author declares no conflict of interest.

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