Environment, Biodiversity & Soil Security

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Nano-Enabled Agriculture Using Nano-Selenium for Crop Productivity: What Needs to be Addressed?

Daniella Sári[1], Aya Ferroudj[1], Arjun Muthu[1], Béni Áron[1], Raziyeh Jamalifard[1],József Prokisch [1], Hassan El-Ramady [1,2],Tamer Elsakhawy [3], Alaa El-Dein Omara [3], and Eric C. Brevik [5]

[1]Institute of Animal Science, Biotechnology and Nature Conservation, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 138 Böszörményi Street, 4032 Debrecen, Hungary
[2] Soil and Water Dept., Faculty of Agriculture, Kafrelsheikh University, 33516 Kafr El-Sheikh, Egypt
[3]Agriculture Microbiology Department, Soil, Water and Environment Research Institute (SWERI), Sakha Agricultural Research Station, Agriculture Research Center, 33717Kafr El-Sheikh, Egypt
[4]College of Agricultural, Life, and Physical Sciences, Southern Illinois University, Carbondale, IL 62901 USA

CROP production requires providing appropriate support for many growth factors, starting with seed germination and proceeding through preparation of the soil for cultivation, growing and development of crops through harvest, and the postharvest period as well. Variables that influence crop growth include all farming management practices, from seed selection to tillage and amendments applied, and also include environmental factors. Biostimulants (BS) have received increasing attention as agricultural amendments, and among BS nano-enabled agro-materials (e.g., nanofertilizers and nanopesticides) have shown potential to improve the efficiency of agrochemical delivery to crops. Several nanoparticles/nanomaterials have proved their potential for promoting crop production under normal and stressful conditions, including nano-selenium (nano-Se). In this review, the agricultural potential of nano-Se was investigated. The potential roles of nano-Se in agro-practices including germination, growth under stressful conditions, and postharvest quality of harvested crops was reviewed. The mechanisms through which nano-Se improves agronomic production may link to its status as an antistressor and ability to improve plant resistance to stresses, its role in controlling several plant enzymatic antioxidants (mainly catalase, superoxide dismutase, and peroxidase), and ability to reduce the generation of reactive oxygen species and H_2O_2. This study highlights the possible role of nano-Se in nano-agriculture especially under climate change and other global crises.

Keywords: Nano-farming, Nano-agriculture, Nano-priming, Nano-pollution, Sustainable farming

1. Introduction

Nano-agriculture is a new approach that applies nanomaterials such as nanofertilizers and nanopesticides to different agro-practices. This can improve the efficiency of agrochemical delivery to cultivated crops (Gomez et al. 2021). Increased interest in nano-agriculture (nano-enabled agriculture) is shown in many recent publications (Adisa et al. 2019). This includes strategies for improved food quality using nano-enabled agro-materials (Gomez et al. 2021), improving plant

*Corresponding author e-mail: ramady2000@gmail.com
Received: 12/04/2023; Accepted: 07/05/2023
DOI: 10.21608/JENVBS.2023.205664.1215

tolerance to abiotic and biotic stresses using nano-enabled agro-materials (Manzoor et al. 2022), entranced accumulation of nano-agro-chemicals in plants (Wu and Li 2022), investigations into the nanotoxicology of nano-enabled materials (White et al. 2022), impacts of nano-enabled agrochemicals on soil microbial communities (Ahmed et al. 2023), and seed treatment using nanomaterials for sustainable agriculture (Shelar et al. 2023). These nano-agrochemicals include organic (e.g., carbon nano dots; Liu et al. 2020) and inorganic (e.g., metallic/ metalloids like nano-selenium; Samynathan et al. 2023) sources that can support crop productivity.

Selenium provides crucial benefits to human and animal nutrition, but its role for higher plants still needs more investigation (El-Ramady et al., 2020). Selenium in nano-form has properties that allow its use in biofortification programs because it supports plant stress tolerance (Samynathan et al. 2023). Nano selenium can be bio-synthetized by many microbes like bacteria (e.g., Bacillus cereus TAH; Ghazi et al. 2022), fungi (Hussein et al. 2022), and plant extracts (Sarkar and Kalita 2022). Green synthesis of selenium nanoparticles (Se-NPs) is not only possible in plant extracts, but also in living organisms (El-Ghamry et al. 2021; Verstegen and Günther 2023). Nano-Se has shown promise in almost all agricultural practices, including seed nano-priming (El-Badri et al. 2021a, 2022), rooting of seedlings (El-Bialy et al. 2023), acclimatization of seedlings (Shalaby et al. 2022), biotic stress resistance (Kang et al. 2022), abiotic stress tolerance such as to drought (El-Saadony et al. 2021), salinity (Shalaby et al. 2021), and heavy metals stress (Zhu et al. 2022), as well as biotic stresses like Xanthomonas albilineans infection (Shi et al. 2023).

This mini-review highlights nano-farming with focus on nano-selenium and its roles managing biotic and abiotic stresses and enhancing a variety of agricultural practices. The discussion will include how nano-germination, nano-stress (biotic/abiotic, and pollution), and nano-postharvest affects the quality of crops.

2. Nano-agriculture: An Overview

Agriculture is an important industry that provides approximately 884 million jobs worldwide (FAO 2020) as well as raw materials (food, feed for our animals, fiber and fuel) that support human life (Brevik et al. 2019). Several farming systems are utilized in modern agriculture, including monocropping (cultivation of only one crop or only one kind of agri-production like crop, livestock, aquaculture, fisheries and forestry production) and multi-cropping (combining crop and livestock production or two or more different cultivated crops that are rotated through given fields) (**Figure 1**). Climate change represents a major challenge for agriculture which threatens environmental protection and human health (Brevik et al. 2022). Farming systems also present a challenge due to pollution generated by many agricultural practices, such as applying manures or sewage to fields that may then end up in river or sea water, burning organic residues and wastes, plastics, and over application of pesticides or fertilizers (**Figure 2**). This pollution is one of many environmental stressors that may negatively affect agricultural production, which also include biotic stresses or pathogens and abiotic stresses (drought, salinity, waterlogging, etc.) (**Figure 3)**. Pollutants may move from its sources to the human food chain through vectors such as acid rain, waterlogged soil and solid wastes, or accumulation of pollutants in crops, which can cause many health problems after consumption of polluted fruits or vegetables. When these pollutants end up in soil and water there is the need for remediation (Münzel et al. 2023), and nanoremediation has shown promise in soil and water media (Ahmed et al. 2021; Behl et al. 2022).

Fig. 1. Farming is a major industry that can make a lot of money conducted properly (photo 1), including in monocropped (photo 2) and multi-cropped (photo 3) systems. Climate change presents a great challenge to farming (photo 4). Sustainable management (photo 5) for environment protection (photo 6) will be important in the future of agriculture. All photos from https://www.pexels.com, except photos no. 2 and 3 which are by El-Ramady.

Fig. 2. Some sources of pollution including throwing the sewage into river or sea water, burning the wastes, plastic pollution, wastes of nuclear factories, pollution of pesticides and over-fertilization. All photos from https://www.pexels.com/ except photo of fertilization from the following link https://www.earth-smart-solutions.com/blogs/blog/foliar-fertilizer-to-improve-plant-health-and-increase-yield.

Fig. 3. Environmental conditions that may stress crops include biotic (pathogens), abiotic (drought, salinity, waterlogging, etc.), and pollution from different sources. Pollutants may be derived from sources like acid rain (1) or waterlogged soil and solid wastes (2). Crops may uptake many kinds of pollutants that can accumulate in their tissues (3). Human consumption these "polluted" fruits or vegetables may cause many health problems (4 and 5), and this may also affect farm animals (6). Photo and drawing by El-Ramady.

Best management practices are a crucial need for crop production using approaches such as precision agricultural technologies (Ahmad and Sharma 2023) or modern applications, including nanomaterials (Abd El-Halim et al. 2022). Nanomaterials can help mediate abiotic (Aguirre-Becerra et al. 2022) and biotic stresses or phytopathogens like Fusarium wilt infection (Abdelraouf et al. 2023). Nanomaterials can also be applied as nanofungicides (Taha et al. 2023). Therefore, a considerable attention has focused on nano-farming possibilities, particularly nano-enabled fertilizers and pesticides (Adisa et al. 2019), nano-enabled agro-strategies to improve food quality (Gomez et al. 2021) and food production (Haris et al. 2023), nano-enabled agro-practices to improve plant tolerance to abiotic stresses (Manzoor et al. 2022), and lignin-based nano-enabled agriculture to deliver nano-agrochemicals (Gigli et al. 2022) such as smart nano-agrochemicals (Sharma et al. 2022, 2023).

3. Nano-selenium for germination

The cultivation of a crop starts with inserting seeds into the soil (**Figure 4**). Germination of seeds depends on many factors including water availability, appropriate temperature, and light. The presence of water supports removal of the seed coat, allowing the conversion of starch into soluble sugars, which the seed embryo needs to form the radical and plumule. Germination under stressful conditions requires more support, something that can be provided by certain nanomaterials. Nano-priming can be used to enhance germination using nanomaterials through a special mode of action (**Figure 5**). This mechanism mainly depends on inducing enhanced expression of aquaporin genes and alteration in seed metabolism, which promotes enzymatic activity to convert stored starch into soluble sugars that move to the embryo. Increasing oxidative respiration and forming reactive oxygen species (mainly H_2O_2), which converted from O_2^- through the enzyme superoxide dismutase, followed by diffusion to the embryo allows interplay between H_2O_2 and phytohormone gibberellic acid (Kandhol et al. 2022).

Many recent studies have illustrated the potential of applied nanomaterials for nano-priming (Anand et al. 2020; Antony et al. 2021; Nile et al. 2022; Khan et al. 2023; Liang et al. 2023). Studies on nano-Se focused on the synergistic role of nano-Se in promoting germination of seeds under stress. Biological nano-Se (150 µmol L^{-1} Se-NPs) mitigated salinity stress during the early seedling stage of rapeseed (*Brassica napus* L.) by enhancing the level of aquaporin genes (BnPIP1-1 and BnPIP2-1), water uptake during the imbibition of seeds, and modulating the uptake of both Na^+ and K^+ (El-Badri et al. 2022). Sarkar and Kalita (2022) reported that applied 30 mg L^{-1} nano-Se alleviated salt stress (200 mM NaCl) in mustard, enhanced phenolic content, the activities of antioxidant enzymes (SOD, CAT, APX, and POX), flavonoid content, and free radical scavenging activity. Nano-Se modulated the expression of gibberellic (GA) and abscisic (ABA) genes during the germination stage of rapeseed under salt stress (El-Badri et al. 2021b).

4. Nano-selenium for stressful conditions

Agriculture is the main source of food and feed for humans and domestic animals. However, agricultural productivity faces several challenges that create stressful conditions for crops, including climate change, pests, and environmental stresses (e.g., drought, salinity, waterlogging), that threaten global food security. At the farm level, more than 22,000 species of phytopathogens, insects, weeds, and mites attack global agro-production (Adisa et al. 2019). Environmental pollution is also a serious threat to the global agro-ecosystem and human health (Brevik et al. 2020) (**Table 1**). Over the last 15 years the Nano-Food-Lab at Debrecen University (Hungary) has investigated substantiable strategies for producing and investigating biological nano-Se at the farm level to promote healthy food production and protect agricultural production from biotic and abiotic stresses (**Figure 6**).

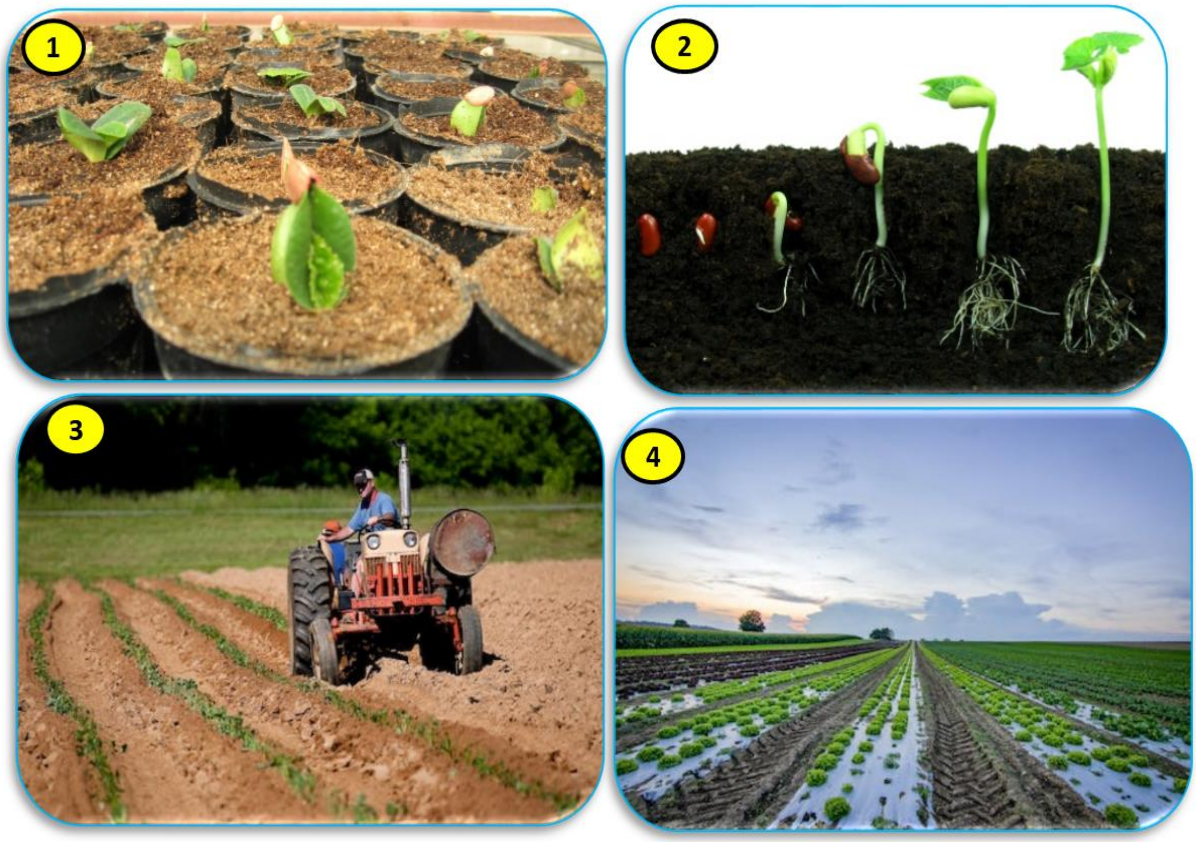

Fig. 4. Seed germination is an important stage of crop production.It is typically first observed when young plants emerge (photo 1). This emergence is followed by several steps leading to formation of true leaves (photo 2). After soil tillage and planting (photo 3), cultivated crops grow until they are harvested (photo 4). All photos from https://www.pexels.com, except photo no. 1 by El-Ramady.

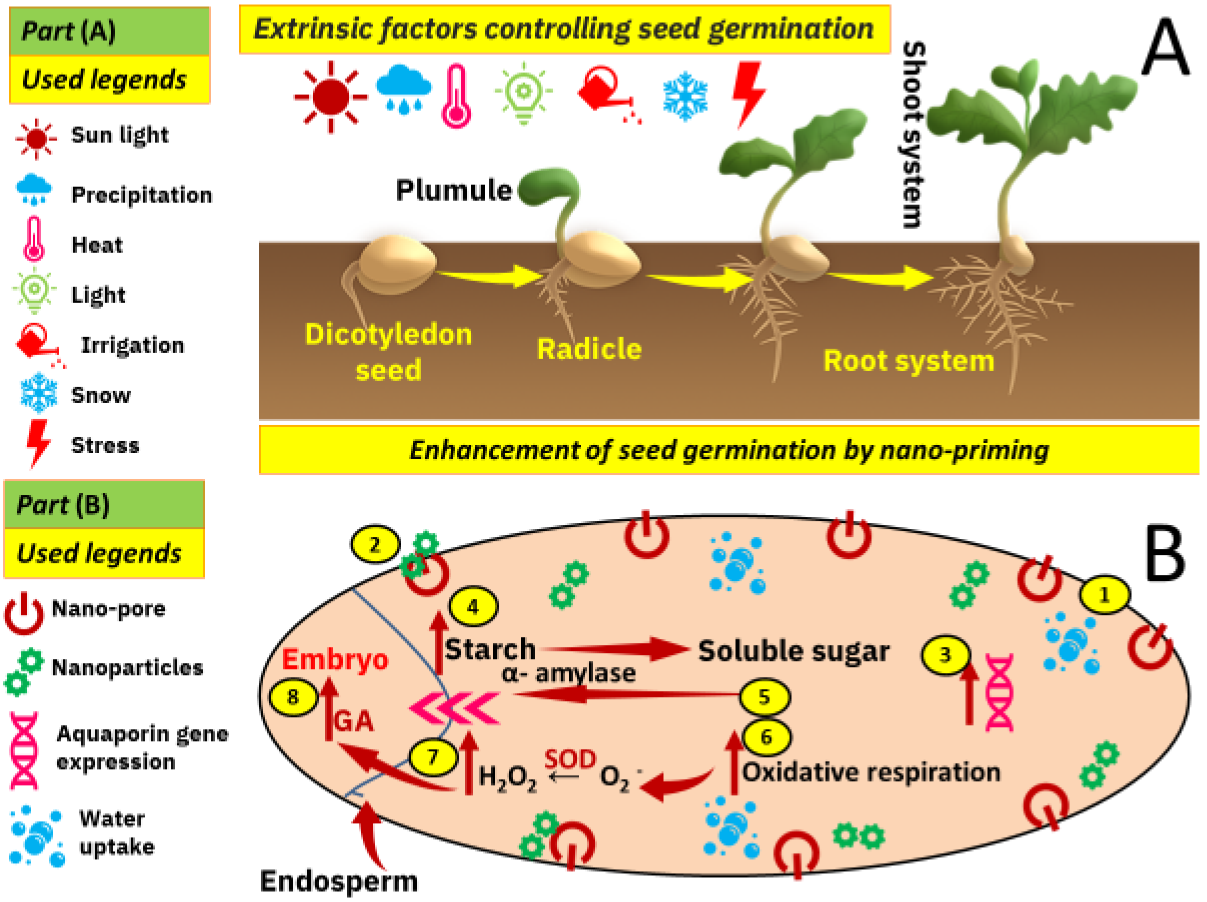

Fig. 5. A. The factors that control seed germination. B: Suggested nano-priming mechanism:soaking seeds with nanoparticles (NPs), followed by high seed uptake of water, allows NPs uptake (step 1 and 2) which reduces stress during germination. NPs also enhance expression of aquaporin genes and alter seed metabolism (3)which enhance enzymatic activity that converts stored starch into soluble sugars (4) andmove to the embryo (5). This increases oxidative respiration and formation of reactive oxygen species (mainly H_2O_2), which convert from O_2^- due to superoxide dismutase (SOD) and H_2O_2 followed by diffusion to the embryo which allows interplay between H_2O_2 and phytohormone gibberellic acid (GA)(Kandhol et al. 2022). Source: image of seed germination from https://www.pexels.com/

Biological nano-Se has gained considerable interest for it ability to increase the Se content of harvested crops like radish (Huang eta al. 2023a), as a biological nano-fungicide to improve yield and quality traits (Taha et al. 2023), or a nano-bactericide for sugarcane (Shi et al. 2023). The entire agricultural calendar has been investigated by applying nano-Se from nano-priming (seed soaking in nano-Se solution) through issues involving postharvest such as improvement of sugar cane juice quality (Shi et al. 2023). The important role of nano-Se is clear when it is applied to cultivated plants that are under biotic or abiotic stresses (**Table 2**).

5. Nano-selenium for postharvest and quality

The quality of crops that make it to market depends on agricultural management (seed selection, fertilization, pesticide use, and other agro-practices) as well as postharvest practices. The main crops include vegetables, fruits, medicinal crops, and the grain crops corn (maize), rice, and wheat (**Figure 7**). Applying nano-Se before harvesting crops has many benefits, including improving crop yield and quality, lower production costs, higher nutrient utilization, and contributing to sustainable production. Nano-Se used as a fertilizer has low toxicity, excellent dispersibility, anti-bacterial ability, and can be applied at low doses compared with traditional mineral Se forms (El-Ramady et al. 2014). Nano-Se can be taken up and assimilated to organic-Se species in plant tissues. It is involved in plant growth and development as well as secondary metabolism (Huang et al. 2023b). The role of nano-Se applied during production to enhancing the postharvest quality of many crops has been reported by several studies on a variety of crops as follows:

1- Nano-Se fertilizers (7.5 mg·L^{-1}) improved summer tea quality by enhancing Se biofortification in tea leaves, reduced catechin and caffeine contents and raise theanine content (Huang et al. 2023b),

2- Exogenously spraying of nano-Se (5.0 mg·L^{-1}) increased sugarcane resistance to *Xanthomonas albilineans* infection by controlling the jasmonic acid

pathway, and improving sugarcane juice quality (Shi et al. 2023),
3- Nano-Se (5.0 mg·L^{-1}) improved antioxidant capacity (i.e., ascorbate peroxidase, β-1,3-glucanase, peroxidase, phenylalanine ammonia lyase, and chitinase activities) in melon plants, enhanced photosynthesis, improved insect resistance of melon plants by increasing cucurbitacin B content in melon plants (Kang et al. 2022),

Table 1. Main effects of soil pollutants on human health, indicating human organs or systems affected and the pollutants causing them (adapted from Münzel et al. 2023).

Human organ or system	Pollutant type	Impacts on human health
Brain	Pb, Mn, Hg, Sn, PBDEs, PAHs, PCBs	Neurodevelopmental impairment, reduction of intelligence quotient, behavioral disorder, Parkinson-type syndrome, headache
Lymph nodes	BTEX, Pb, PFAS, PCBs	Altered immune response, reduced response to vaccines in children
Thyroid	Cd, PCBs, PDBEs	Altered metabolism and reproductive hormone levels, Reduced thyroid hormones, altered growth
Heart and cardiovascular	Benzene, Pb, Hg, organochlorine pesticides, PAHs, PCBs,	Microplastics hypertension, endothelial dysfunction, vascular inflammation, oxidative stress, atherosclerosis
Lungs	As, Cd, Cr, Cu, Hg, Rn, asbestos	Pulmonary emphysema, asthma, chemical pneumonia, lung cancer, mesothelioma
Stomach	N, ionized radiation	Stomach cancer
Pancreas	Phthalates, PCBs	Altered insulin metabolism, adipogenesis, diabetes
Liver	Cr, Cu, DDT, PAHs, PCBs, PFAS, phthalates	Increased cholesterol levels, liver cancer, elevated hepatic enzyme levels, necrosis
Kidneys	Cd, Pb, Hg, PAHs, PFAS	Renal tubular dysfunction, kidney weight changes, progressive nephropathy, chronic inflammation, kidney cancer
Intestines	As, Cu, Pb, Hg, Sn, POPs, micro-plastics	Nausea, vomiting, diarrhea, cancer of gastrointestinal system, adnominal pain and cramping
Bladder	As, Pb	Cancer of urinary bladder, urinary changes
Reproductive system	Sb, Pb, Mn, asbestos, phthalates, PBDs, PCBs, PFAS	Testicular atrophy, early menopause, reduced testosterone, reproductive alternations, decreased libido, impotence, sexual dysfunction, endometriosis, hormonal cancers (breast, prostate, testes), infertility, ovary cancer
Bones and joints	Cd, Pb, Rd, PCPs	Impaired bones development, slow growth, changes in metabolism of calcium and bone formation, osteomalacia, bone cancer
Skin	As, Cd, PAHs, PCBs	Hyperkeratosis, hyperpigmentation, hypopigmentation, skin irritation and inflammation, chloracne, hirsutism, abnormalities in skin, tooth, and nail

4- Nano-Se (1.0 mg·L^{-1}) repairs tomato fruits at the immature green stage and their flavor quality under penthiopyrad stress as a chiral carboxamide fungicide by reducing the MDA content and phytotoxicity resulted from this fungicide, and by increasing the contents of volatile compounds, soluble sugars, and nutrients (Liu et al. 2022),
5- Nano-Se (10 mg·L^{-1}) promoted quality of *Salvia miltiorrhiza* (as a valuable traditional Chinese medicine), by stimulating plant growth, antioxidant capacity, and the accumulation of tanshinones and salvianolic acids by activating the salicylic acid and jasmonic acid signaling pathways, and reducing the survival and fecundity of aphids (Zhang et al. 2023),
6- The quality of strawberry seedlings also was improved by applying biological nano-selenium (100 mg L^{-1}) by improving the growth, photosynthetic pigments, antioxidant content (catalase, polyphenol oxide, and peroxidase), and nutritional status (contents of NPK, Cu, Mn, Zn, and Se) of the seedlings compared to the control (El-Baily et al. 2023),
7- The bio-nano-Se improved the radish yield, nutritional quality and selenium content by increasing the dry matter content, reducing sugar content, soluble solid content, the content of soluble sugar, but the water-soluble protein and the vitamin C content were decreased (Huang et al. 2023a),

8- The combined application of bio-nanofertilizers of Se (100 mg L^{-1}) and nano-CuO (100 mg L^{-1}) enhancing tomato productivity and quality under saline irrigation water stress by increasing tomato fruit quality (vitamin C, firmness and fruit yield), plant enzymatic antioxidants (enzymatic antioxidants (catalase, peroxidase,and polyphenol oxidase), although the negative impact of saline water on soil biological activity (soil microbial counts and enzymes including soil enzyme activities including dehydrogenase and urease) at harvesting (Saffan et al. 2022),

9- Combined biological nanofertilizers of Se (100 mg L^{-1}) and nano-CuO (100 mg L^{-1}) enhanced the growth of banana seedlings by increasing the survival rate, photosynthetic pigments and antioxidant enzymatic activities (CAT, PPO, and POX) for their acclimatization (Shalaby et al. 2022), and,

10- Exogenous application of nano-Se (10 µM nan-Se) improved secondary metabolites in lemon verbena under salinity (from 40 to 160 mM NaCl) by reducing leaf electrolyte leakage, and the accumulation of malondialdehyde, and H_2O_2, enhanced the biosynthesis of secondary metabolites (e.g., total phenolic content, essential oils, and flavonoid compounds) under salinity conditions (Ghanbari et al. 2023).

6. Conclusions and further prospects

The humanity faces a great challenge representing in how to save the enough and safe foods to feed the entire the global population. Farming is the main source for such food, which may face several problems suppressing the farming productivity such as climate change, and pollution. The management of farming to solve such previous problems needs sustainable approaches like biological nano-approaches (e.g., biological nano-Se).

Nano-Se have proved its potentiality against biotic and abiotic stresses and promoting crop production. Selenium based nanoparticles also have proved its importance for several farming practices under stressful conditions involving seed germination, growing stages, flowering and post-harvesting as well. Applying biological nano-Se to different farming issues that corresponding with the crop, and animal farming has an opened research area which still needs more investigations.

The great challenge that still faces the global farming is how to get the sustainable farming under the climate change, which is requested to decrease the CO_2, and re-activate the recycling approach all over the world. On the other hand, the nano-pollution on the farm level also still needs more studies especially under the over-doses of nanomaterials many agro-issues.

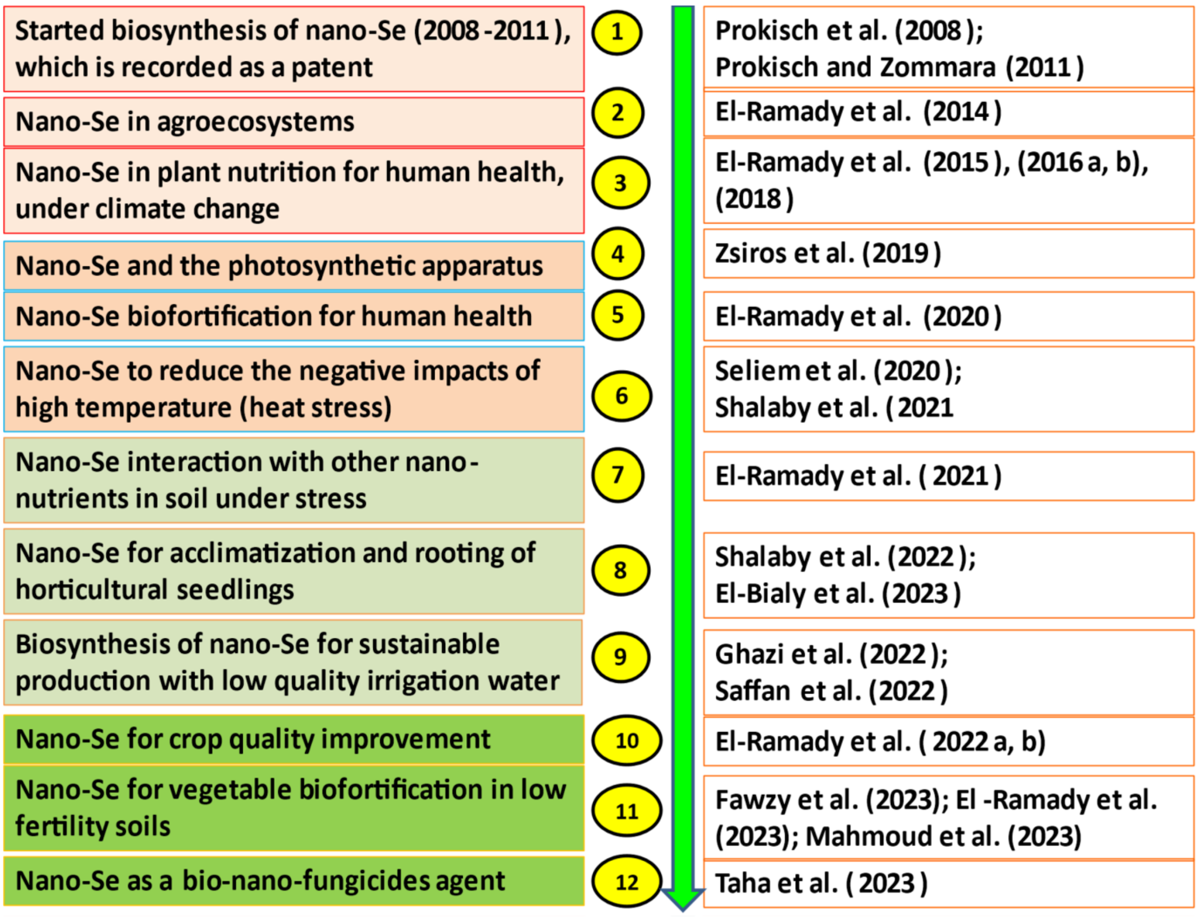

Fig. 6. A timeline for research into bio-nano selenium for crop production at Debrecen University, Hungary, starting with biological synthesis of nano-Se and continuing through our recent research on nano-Se.

Table 2. Main response of cultivated plants to stress after applying nano-Se on the farm level.

Plant species	Stress type	Se-NPs dose	Main response	Refs.
Tomato (*Solanum lycopersicum* L.)	Penthiopyrad (Pen) fungicide	1.0 mg L^{-1} Se-NPs	Repaired inhibitory effects of Pen on fruit growth and flavor quality	[1]
Melon (*Cucumis melo* L.)	Biological stress (powdery mildew)	Doses: 2.5, 5.0, and 10.0 mg·L^{-1}	Reduced plastio-globulin in leaves, prevented pathogen infection by increasing cucurbitacin B	[2]
Radix (*Salviae miltiorrhizae* et Rhizoma) Danshen	Biological stress (aphids)	Nano-Se at 10 mg L^{-1}	Promoted product quality and plant defense by inducing accumulation of tanshinones and salvianolic acids	[3]
Sugarcane (*Saccharum* spp. hybrids)	Leaf scald disease (*Xanthomonas albilineans* L.)	Doses: 5.0, and 10.0 mg·L^{-1}	Enhanced plant quality and resistance to infectionwhen used as a nano-bactericide by reducing ROS and H_2O_2 accumulation	[4]
Pak choi (*Brassica chinensis* L.)	Heavy metals stress (Cd, Pb, and Hg)	Doses: 5.0, 10.0 and 20.0 mg·L^{-1}	Activated antioxidant system, reduced MDA level, increased SeMet, SeCys2, and SeMeCys contents in shoots	[5]
Common Bean (*Phaseolus vulgaris* L.)	Alternaria leaf spot disease (*A. alternata*)	Dose up to 100 mg·L^{-1}	Supported growth and yield when applied as a nano-fungicide by increasing enzymatic capacity and antioxidant activity and decreasing disease severity	[6]
Cucumber (*Cucumis sativus* L.)	Soil salinity (EC 4.49 dS m^{-1}); heat stress (41 ℃)	Nano-Se at 25 mg L^{-1}	Increased enzymatic antioxidant capacities and marketable fruit yield and yield quality (fruit firmness &TSS) compared to the control	[7]
Tomato (*Solanum lycopersicum* L.)	Saline irrigation water (2.84 dS m^{-1})	Nano-Se at 25, 50 and 100 mg L^{-1}	Combined Se and CuO nanofertilizers promoted tomato yield under saline water irrigation	[8]
Rapeseed (*Brassica napus* L.)	Salinity stress	Bio nano-Se at 150 µmol L^{-1}	Modulated the uptake of Na^+ and K^+; prevented oxidative damage by salinity, and boosted seed germination and crop productivity	[9]
Moldavian balm(*Dracocephalum moldavica* L.)	Cadmiumtoxicity stress (2.5 and 5.0 mg kg^{-1})	Chitosan-Se NPs (5 and 10mgL^{-1})	Enhanced photosynthetic pigments, chlorophyll fluorescence, proline, phenols, antioxidant enzymes activities	[10]

List of refs.: [1] Liu et al. (2022), [2] Kang et al. (2022), [3] Zhang et al. (2023), [4] Shi et al. (2023), [5] Zhu et al. (2022), [6] Taha et al. 2023, [7] Shalaby et al. (2021), [8] Saffan et al. (2022), [9] El-Badri et al. (2022), [10] Azimi et al. (2021)

Fig. 7. Crop production depends on overall growing practices, including the harvesting process and postharvest practices. Important crops include fruits, vegetables (photos 1, 2), and grain crops like rice (photo 5) and wheat (photo 6). Photo source from 1 to4https://www.pexels.com/, 5 and 6 from E.C. Brevik.

Ethics approval and consent to participate: This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication: All authors declare their consent for publication.

Funding: This research was supported by the Stipendium Hungaricum Scholarship Program.

Conflicts of Interest: The author declares no conflict of interest.

Contribution of Authors: All authors shared in writing, editing and revising the MS and agree to its publication.

Acknowledgments: This research was supported by the Stipendium Hungaricum Scholarship Program.

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