

## A Review of the Selenium Nanoparticles in the Promotion of Crops Growth and Antimicrobial Defence.

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**Abstract:** Nanotechnology is now an interdisciplinary prospective technology that is vastly utilized in agriculture, environmental science and biomedicine. Selenium nanoparticles (SeNPs) are some of the nanomaterials which have gained great interest in the research because of their distinct physicochemical characteristics such as high surface area, reactivity and biological activity among others in contrast with bulk selenium compounds. Selenium is a crucial trace mineral, which participates in redox signalling and antioxidant protection systems; nevertheless, regular forms of selenium in practice have a small range between the positive and negative concentrations. Selenium nanoparticles have been developed and offer a good alternative that is better-toxicity-and-better-bioavailability.

The present review gives a detailed description of the synthesis, characterization, and biological uses of the SeNPs with specific focus on its ability to regulate plant growth and its use as a mode of antimicrobial resistance. Several synthesis methods are discussed such as physical, chemical, and green biological methods, the microbial and the plant-mediated synthesis methods have been discussed, and they both provide environmentally friendly and sustainable nanoparticles synthesis methods. The review goes on to discuss the process by which SeNPs can affect plant physiology, including stimulated nutrient uptake, increased photosynthetic efficiency, regulation of primary metabolism, and stimulation of antioxidant responsiveness during abiotic stress, such as drought, salt hostilities and heavy metal toxicity.

Besides, the antimicrobial properties of the SeNPs against bacterial and fungal pathogens are considered, including the mechanisms of membrane disruption, generating reactive oxygen species in the cell, disrupting macromolecular synthesis, and preventing biofilm formation. The ability of SeNPs to be used as nano-fertilizers and nano-pesticides underlines why they may be used in sustainable agriculture. Lastly, the constraints are nowadays, biosafety issues, and future prospects of the large-scale farms utilizing selenium nanoparticles are

addressed. Altogether, SeNPs are promising nanomaterials to promote the productivity and the well-being of crops and facilitate ecologically viable agricultural activities.

**Keywords:** Selenium nanoparticles (SeNPs), nanotechnology in agriculture, plant growth promotion, antimicrobial activity, abiotic stress tolerance, nano-fertilizers, green synthesis, sustainable agriculture

### I. Introduction

It is in nanotechnology that the term has gained popularity as a fast developing interdisciplinary science that has many applications in the industry of agriculture, the environment, and biomedicine. Nanomaterials in the range of 1 to 100 nm have a special physicochemical character differentiating a high surface area, high activity as catalyst, and reactivity relative to bulk material (Kah et al., 2018). Nanotechnology is also being implemented in agricultural systems in the production of nano-fertilizers, nano-pesticides, and nano sensors to enhance efficiency of nutrient consumption and productivity of crops and enable precision of agriculture systems (El-Ramady et al., 2016). These nanomaterials help in targeted delivery and controlled release of agrochemicals thus preventing the environmental contamination and enhancing sustainability in crop production. Besides their application in agriculture, nanoparticles have also acquired enough significance in the biomedical field in drug delivery, antimicrobial agents, and diagnostic imaging systems due to their excellent property to interact with microbial cells and biological membranes (Rai et al., 2016; Nikalje, 2015).

Selenium (Se) is a very critical micro-nutrient that is of great importance in controlling biological processes that take place in humans and animals especially in antioxidant defence and in the redox state of cells. The selenium is included in a complex of selenoproteins including glutathione peroxidase and thioredoxin reductase which help in

the protection of the cells against oxidative damage by counteracting the reactive oxygen species (ROS) (Rayman, 2012). Despite the fact that selenium is not regarded as an essential nutrient in most plants, low levels have been described to trigger plant growth, enhance antioxidant enzyme activities, and tolerance to abiotic stresses, including drought, salinity, and heavy metal toxicity (Gupta and Gupta, 2017). Also, enrichment of crops with selenium has become a major concern as a method to overcome selenium shortage in patients, particularly the areas with a low production of dietary selenium (Hasanuzzaman et al., 2020; El-Ramady et al., 2016).

Traditional selenium fortification at the farm and biological sentry level usually entails the use of inorganic selenium salts which comprise sodium selenite and sodium selenate or bulk selenium. Nevertheless, they frequently have low therapeutic index and, therefore, are not safe to use in biology due to their small therapeutic index (El-Ramady et al., 2016). Overload of selenium could lead to phytotoxicity, oxidative stress and environmental issues. Selenium nanoparticles (SeNPs) present an appealing alternative in recent years as it has better physicochemical properties, such as a high surface-to-volume ratio and better biological activity (Wadhvani et al., 2016). Furthermore, it has been shown that SeNPs are more bioavailable and less toxic than traditional selenium compounds and hence can be used in farming and biomedical applications (Menon et al., 2019; Ikram et al., 2021).

Selenium nanoparticles have recently caused a lot of interest in the field of multifunctionalities in enhancing plant growth and antimicrobial protection against phytopathogens. SeNPs have been suggested to promote seed germination, photosynthetic efficiency, and stimulate antioxidant defence mechanisms in plants, which make the plants more robust to environmental stresses (Hussein et al., 2019). Moreover, selenium nanoparticles have a high antimicrobial effect against diverse bacterial and fungal pathogens by disruption of cell membranes, generating oxidative stress, and disrupting metabolic pathways of microbes (Ikram et al., 2021). Given the growing research attention on selenium-based nanomaterials, there is a need to consider their modes of synthesis, their biological attributes and possible use in agriculture. Thus, the purpose of the review is to present an in-depth picture of selenium nanoparticles with specific emphasis on their functionality in relation to the promotion of plant growth and antimicrobial protection systems as

part of a sustainable agricultural system (Hasanuzzaman et al., 2020; Wadhvani et al., 2016).

## II. Preparation and Characterization of Selenium Nanoparticles.

Both the formation and characterisation of the selenium nanoparticles (SeNPs) must be critical steps that dictate the physics-chemical characteristics and stability of these nanoparticles as well as their functionality with the body. Several synthesis techniques have been established such as traditional physical and chemical, and green synthesis, to obtain SeNPs of size, shape, and surface attributes under control. These synthesis methods have a major impact on reactivity, bioavailability and the biomedical and agricultural use of the nanoparticles. Besides the synthesis, the complete characterization of SeNPs is necessary to ensure that they are formed and to learn their structural, optical, and surface characteristics. Complex analytical tools like the UV-Vis spectroscopy, FTIR, XRD, electron microscopy, and particle size analysis will give specific information about the morphology, crystallinity, and stability of nanoparticles. Combinations of these methods allow improving the performance of SeNPs in different scientific and industrial applications.

### 2.1 Synthesis Methods: Conventional format Synthetic methods

Selenium nanoparticles can be prepared in different traditional methods such as physical and chemical methods whereby it is possible to control the manner in which nanoparticles are made in terms of size and morphology. Nanoparticles made by high-energy processes in which nucleation and growth of elemental selenium is promoted in the presence of precursor materials are generated by these physical synthesis techniques: laser ablation, hydrothermal processing, and microwave irradiation (Wadhvani et al., 2016). The methods are typically capable of producing nanoparticles with a well-defined structure, which are highly pure and therefore a challenge to counterfeit or mask, but they can be very costly in instrumentation and require the input of high energy to operate, limiting their large-scale use (Ikram et al., 2021)

Chemical synthesis is one of the most popular approaches to the generation of SeNPs and a typical procedure that consists in reducing selenium salts, like sodium selenite or sodium selenate, with the help of chemical reducing agents. In order to produce elemental nanoparticles out of selenium ions, the reduction of such agents as ascorbic acid, hydrazine, and sodium borohydride is involved

(Menon et al., 2019). The prevention of aggregation and the provision of colloidal stability is often achieved with stabilizing agents like polymers or surfactants, but toxic chemicals and dangerous by-products are used to achieve this effect, which is questionable with regard to environmental safety and biocompatibility (El-Ramady et al., 2016).

## 2.2 Green Synthesis of Selenium Nanoparticles

Green synthesis is the new system that will be environmentally friendly to use in developing nanoparticles since biological material is used as a reducing agent and stabilizing agent. Natural capping may be used to reduce selenium ions to stabilize the nanoparticles resulting from the system by biological molecules, including proteins, polysaccharides, enzymes, and phenolic compounds (Wadhvani et al., 2016). Most of these reactions take place under mild conditions, including ambient temperature and neutral pH, as a consequence of which green synthesis is a safer and more energy-efficient process than traditional physical or chemical counterparts (Hasanuzzaman et al., 2020).

Also, it acts as an environmental advantage in that green synthesized selenium nanoparticles have enhanced biocompatibility and biological activity because of the existence of biomolecules on the nanoparticle surface. Surface-bound compounds have the potential to improve the effects of antioxidant and antimicrobial actions, which can be considered more useful in agriculture and biomedical work (Ikram et al., 2021). Therefore, biologically synthesized SeNPs have undergone a good representation in the use in plant growth promotion, crop protection and therapeutic studies (Hussein et al., 2019).

### 2.2.1 Microbial Synthesis (Bacteria, Fungi, Algae)

The third type of synthesis is what is known as Microbial Synthesis and this process does not involve the use of chemical compounds but follows the cellular processes and the presence of oxygen. Selenium oxyanions can be reduced by enzyme activities of microorganisms like bacteria, fungi, and algae into elemental selenium nanoparticles. Selenite ( $\text{SeO}_3^{2-}$ ) and selenate ( $\text{SeO}_4^{2-}$ ), which are toxic forms of selenium, are reduced to elemental selenium as part of the detoxification workers during microbial metabolism (Wadhvani et al., 2016). This is the biotransformation reaction that is catalyzed by enzymes like reductases and electron transport proteins, which can help to transform selenium ions into forms of nanoparticles (Ikram et al., 2021).

The production of selenium nanoparticles with various morphological features typically has been reported in several microbial species such as *Bacillus*, *Pseudomonas* and *Aspergillus*. The fungal systems are especially productive since they release substantial concentrations of extracellular enzymes and metabolites that help to develop nanoparticles (Menon et al., 2019). Likewise, the synthesis through algae has attracted the interest of scientists because of the existence of a variety of biomolecules that could reduce selenium ions and stabilize nanoparticles (Zhang et al., 2019).

### 2.2.2 Phytosynthesis of Plant Extracts as Reducing and Capping Agents.

Phytotransduction (plant-mediated synthesis or phytosynthesis) is currently one of the most popular green synthesis approaches to selenium nanoparticles. Plant extracts are also a source of bioactive phytochemicals, such as flavonoids, phenolics, terpenoids, alkaloids, and proteins, which perform the roles of reducing and stabilizing the formation of nanoparticles (Hussein et al., 2019). These chemicals help in reducing selenium ions into elemental selenium and at the same time act as a coating on top of the nanoparticles to protect them (Hasanuzzaman et al., 2020).

Numerous medicinal plants have been effectively utilized in the production of selenium nanoparticles and it includes *Azadirachta indica*, *Allium sativum*, *Zingiber officinale* and *Piper betle*. Phytochemicals found in these plant extracts are strong antioxidants that help in efficient formation and stabilisation of nanoparticles (Kumar et al., 2020). Specifically, flower extracts of *Calotropis gigantea* include flavonoids, phenolic compounds and cardiac glycosides that may be used in the reduction and stabilization of selenium nanoparticles, in addition to improving their antimicrobial and antioxidant characteristics (Ikram et al., 2021).

## 2.3 Major Characterization Method (UV- Vis, FTIR, XRD, SEM/TEM, DLS) Zeta Potential.

Once the selenium nanoparticles have been synthesized, they have to be analyzed by a number of analytical methods to understand their optical aspects, morphology, crystallinity and surface chemistry. UV-Visible spectroscopy is often a preliminary method that is used to verify the formation of nanoparticles by the identification of specific absorption peaks, which in the case of selenium nanoparticles are usually within the 250-350 nm wavelength range (Menon et al., 2019). The emergence of this absorption band is a sign of the

nucleation and stabilization of selenium nanoparticles in the colloidal suspension (Wadhvani et al., 2016).

FTIR is commonly utilized in the identification of functional groups on the surface of the nanoparticle, which are products of biomolecules that were engaged in the reduction and adcoating processes. The presence of characteristic peaks related to O-H, N-H, C=O and C-O groups is a sign of phenolics, proteins, and other phytochemicals that stabilize nanoparticles (Hussein et al., 2019). The crystalline state of selenium nanoparticles is also analyzed by X-ray crystallization (XRD) as the indicator of the presence of elemental selenium structures (Kumar et al., 2020). Microscopic imaging like Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) can be used to give critical information about the morphology and distribution of nanoparticles in terms of size. These imaging methods allow obtaining a picture of the shape and surface structure of nanoparticles in the nanoscale (Ikram et al., 2021). Furthermore, the particle size distribution in suspension is determined with the help of the Dynamic Light Scattering (DLS) method, whereas the surface charge and colloidal stability of nanoparticles are measured by the use of zeta potential (Zhang et al., 2019).

### III. Plant Growth and Physiology in NPs.

Selenium nanoparticles (SeNPs) have become significant nanomaterial that can impact plant growth and physiological functions on different scales. SeNPs are easily absorbed by plants and translocated to various tissues and absorbed by plants since they are at the nanoscale and reactive, and also can be taken up by plants and incorporated into metabolic pathways. The attributes allow them to adjust important physiological processes, such as nutrient uptake, photosynthesis, and the mechanism of stress response. Moreover, SeNPs are important in boosting the development of plants through increased seed germination, growth in roots and shoots, and total biomass. They also help to cause tolerance to abiotic stresses as well as regulate antioxidant defence systems and thus keeps the cell homeostatic. All this means that SeNPs can be used as a promising delivery system to enhance plant development, yield, and adaptability to different environmental factors.

#### 3.1 Uptake, Translocation, and Accumulation Mechanisms.

Selenium nanoparticles (SeNPs) may enter plants mostly via root uptake in which the particle is

believed to enter the root epidermal cells and then takes up the apoplastic and symplastic route. Research has indicated that smaller nanoparticles that have reduced diameter are more mobile in plant tissues because they are more reactive to the surface and can pass through cell walls pores (Qin et al., 2025). Having been absorbed, SeNPs can be carried by the xylem to the aerial tissues such as leaves and reproductive organs (Ikram et al., 2021).

In plant cells, selenium nanoparticles may be biotransformed into organic selenium products selenomethionine and selenocysteine that integrate into plant proteins (White, 2018). All these changes enable selenium to be involved in physiology such as antioxidant metabolism and redox regulation (Hasanuzzaman et al., 2020). Moreover, the close proximity between selenium and sulfur metabolism allows plants to operate with the help of sulfur transporters in the assimilation and translocation of selenium in plant tissues (Gupta and Gupta, 2017).

The amount of selenium accumulated in the plant organs is different in relation to the size of the nanoparticles, the concentration of the nanoparticles, and the species of the plants. According to a number of studies, roots are generally known to have a greater accumulation of selenium compared to shoots as root is the main point of contact with a nanoparticle in terms of nanoparticle uptake (Ikram et al., 2021). Nonetheless, its translocation to leaves and edible tissues are also possible under favorable physiological environments, and this has some implication on the molecular aspects of plant nutrition and on crop biofortification practice (Qin et al., 2025).

#### 3.2 Morphological Effects: The germination of seeds and the development of roots/ shoots.

It is common knowledge that selenium nanoparticles affect early plant development stages especially seed germination and seedling growth. Subsequent germination in low amounts of SeNPs is capable of inducing the activity of hydrolytic enzymes in the mobilization of carbohydrates during the metabolism of the seed (Rastogi et al., 2019). The better germination rates might be also due to the increase in the membrane stability and the augmented absorption of water in the treated seeds (Hasanuzzaman et al., 2020).

SeNPs also interfere with the morphology of plants by enhancing the growth of roots and shoots. Several crop species have reported an increase in root length and biomass after applying the SeNP, and this effect can be linked to the fact that the use of the product stimulated the cell division and elongation

processes (Ikram et al., 2021). Enhanced root structure enhances nutrient uptake rate and promotes favorable growth of plants both in normal and stressful environment (Gupta and Gupta, 2017).

Besides stimulating the vegetative growth, the treatment of SeNP is capable of enhancing the overall plant health and yield. It has been proved by experimental studies that the highest level of selenium nanoparticle results in increased leaf development, a higher plant height, and biomass accumulation compared with plants treated with nothing (Qin et al., 2025). These results point to the possibility of SeNPs being useful as plant growth stimulants under the condition of being used in reasonable amounts.

### 3.3 Photosynthetic pigments and primary metabolism Modulation.

Photosynthetic performance can be greatly affected by the effects of selenium nanoparticles on plants. Plants watered with SeNPs have been shown to increase the concentration of chlorophyll a and chlorophyll b, which is why the photosynthetic capacity and light-harvesting efficiency improve (Hasanuzzaman et al., 2020). The protective effect of selenium on stabilization of chloroplast membranes and minimizing oxidative injury in photosynthetic tissues is also believed to enhance this (White, 2018).

Primary metabolic processes, such as carbohydrate metabolism, amino acid production and lipid production, are also influenced by SeNPs. Optimal levels of selenium nanoparticles have been found to enhance the accumulation of carbohydrates in plants as well as enhancing their nitrogen acquisition (Rastogi et al., 2019). The changes in the metabolism promote the growth and productivity of the plant.

Moreover, Selenium nanoparticles are reported to exert regulation on metabolic pathways regulating stressful tolerance and metabolism of energy. SeNPs are known to keep cellular redox equilibrium in place and enhance enzyme performance by allowing plants to maintain metabolic efficiency in rather adverse environmental conditions (Qin et al., 2025).

### 3.4 Abiotic Stress Mitigation (Drought, Salinity, HeavyMetals) SeNPs.

Drought, salinity, and toxicity caused by heavy metals are abiotic stresses that restrict the productivity of plants in the world. It is demonstrated that selenium nanoparticles increased the tolerance of plants to these stresses through protection mechanisms being physiological and biochemical

(Hasanuzzaman et al., 2020). As an example, SeNP therapy can augment osmotic adjustment, augment the concentration of compatible solutes like proline and soluble sugars (Gupta and Gupta, 2017).

SeNPs can ensure the ionic balance during salinity stress by controlling the movement of sodium and potassium in the plant tissue. The regulation mitigates the harm caused by salt and enhances stability of the membranes of stressed plants (Rastogi et al., 2019). Moreover, SeNPs are capable of alleviating the stress caused by drought via enhancing the efficiency of water-use and stomatal control (White, 2018).

The Selenium nanoparticles are also significant in eliminating the toxicity of the heavy metals. It has also been shown that the use of SeNPs could reduce the absorption of and translocation of harmful metals in plants, including cadmium and lead (Ikram et al., 2021). The protective effects of these take place in terms of increased antioxidant defence, and control of metal-detoxification mechanisms.

### 3.5 Plant antioxidant defence Systems (Enzymatic and Non-enzymatic ROS Scavenging) Regulation.

The excess of reactive oxygen species (ROS) is one of the typical effects of the environmental stress in plants. Selenium nanoparticles also play a role in improved antioxidant defence by increasing the action of enzyme antioxidants including superoxide dismutases, catalase, and peroxidases activities (Hasanuzzaman et al., 2020). These are enzymes that remove the effects of the reactive oxygen species and safeguard the structures of the cell against any oxidative damage.

SeNP treatment also improves non-enzymatic antioxidant systems such as glutathione, ascorbate and phenolic compounds (Rastogi et al., 2019). These molecules act as redox buffers which stabilize cellular homeostasis and they avert oxidative stress. SeNPs can be applied to enhance the activity of enzymatic and non-enzymatic antioxidants to ensure physiological stability and metabolic efficiency of plants in stressful environments (White, 2018).

## IV. SeNPs have antimicrobial activity.

Selenium nanoparticles (SeNPs) have become of great interest because of its strong antimicrobial effect against various bacterial pathogens especially the broad spectrum of pathogens. They are highly reactive on their surface and of nanoscale which allows them to interact with cell membrane of the microbes to cause structural

damage and inhibit cellular functions. The efficacy of SeNPs against Gram-positive and Gram-negative bacteria depends on the particle size, the surface charge, and concentration that affect the antibacterial ability of SeNPs. Due to their extensive range of activity and some unexpected mode of action, SeNPs are yet to be exploited as promising alternatives to traditional antibiotics in agriculture and human medicine.

#### 4.1 Antibacterial Activity

Selenium nanoparticles have very good antibacterial property with respect to its high surface reactivity and its ability to engage with the membranes of the microbes. The research has indicated that SeNPs have had the capability to prevent the growth of bacteria by breaking the integrity of cell membranes and by disrupting cellular metabolism (Menon et al., 2022). The above antimicrobial effects depend on the size of nanoparticles, their surface charge and concentration.

SeNPs had been shown to be active against many bacterial disease-causing agents such as *Escherichia coli*, *Pseudomonas aero*, and *Staphylococcus aureus* (Martinez-Esquivias et al., 2021). Their antimicrobial action is widely broad-spectrum and thus promising as alternatives to traditional antibiotics, in the farming and medical fields. The drug has demonstrated efficacy against Gram-positive Bacteria, although there is a lack of adequate clinical study data presently available in the research literature. Efficacy against Gram-positive Bacteria. The drug has been shown to be effective against Gram-positive Bacteria, but presently, there is insufficient clinical research data in the world literature.

The cell wall is composed of thick peptidoglycan, and the gram-positive bacteria which are able to react with selenium nanoparticles strongly. SeNPs have an ability to adhere to cell wall components and rupture of the membrane integrity, causing leakage of intracellular materials (Menon et al., 2022). The ultimate effect of interaction with the nanoparticles is structural damage resulting in the ultimate death of bacterial cells. It has been shown that Gram-positive bacteria like *Staphylococcus aureus* and *Bacillus subtilis* are highly inhibited by SeNPs (Martinez-Esquivias et al., 2021). These results suggest the use of SeNPs as antimicrobial agents to control pathogenic bacteria.

#### 4.1.2 The efficacy of calcium channel blockers against Gram-negative Bacteria.

The gram-negative bacteria has an outer membrane that is capable of providing resistance towards antimicrobial agents. Having this obstacle, selenium nanoparticles have been observed to be able to cross the outer membrane to disrupt the structures in the cells (Menon et al., 2022). Interaction between SeNPs and membrane proteins as well as lipopolysaccharides causes an increase in membrane permeability.

#### 4.2 Antifungal Effect on Phytopathogen and Human Pathogen.

Selenium nanoparticles are also known to have potent antifungal properties on a number of plant and human pathogenic fungi. SeNPs have the ability to suppress spore germination and hyal growth of fungus including *Fusarium*, *Aspergillus*, and *Candida* species (Ikram et al., 2021). Much part of these antifungal actions can be associated with the destruction of membranes and the stimulation of oxidative stress.

SeNPs have been explored as possible agents of crop disease control of fungal diseases that result in significant losses in agricultural production. The fact that they are capable of their action not only of preventing fungal development but also with comparatively low toxicity to plants also makes them a desirable candidate in plant protection methods that are friendly to the environment (Rastogi et al., 2019).

#### 4.3 Mechanism of Actions of Antimicrobial Agents.

This process consists of cell wall degradation and membrane permeabilization (Hayes et al., 2018). Direct contact of the SeNPs was detected with the cell wall and membrane of microbial cells leading to structural disturbance and transparency (Menon et al., 2022). Such interactions cause a leakage of the intracellular contents and eventual cell death of the microbials.

#### 4.3.1 Production of intracellular ROS and Oxidative Stress.

SeNPs induce the production of reactive oxygen species in the microbial cells. The large production of ROS harms proteins, lipids, and nucleic acids, causing oxidative stress and death in the microbes (Martinez-Esquivias et al., 2021).

#### 4.3.2 Interaction with intracellular macromolecules (DNA, RNA, Proteins).

The nanoparticles of selenium are capable of getting attached to microbial DNA, proteins and disrupting vital cellular activities like replication and transcription (Ikram et al., 2021). Such interactions interfere with the microbial metabolism and put the cell growth at bay.

#### 4.3.3 Interference with ATP production.

SeNPs may impair the energy metabolism in cells through disrupting electron transport chains and ATP synthesis pathways of microbial cells (Menon et al., 2022). Since less ATP is produced, this causes metabolic failure and death of microbes.

#### 4.3.4 Anti-biofilm properties of the SeNPs.

Biofilms are microbial communities which are extremely resistant to antimicrobial agents. Selenium nanoparticles were found to prevent biofilm formation through adhesion-related and quorum sensing-related disruption in microorganisms (Martinez-Esquivias et al., 2021).

Further, SeNPs are able to enter into the preexisting biofilms and cause oxidative injury to the entrenched microbial cells. Such characteristics render selenium nanoparticles promising agents to be used in the control of biofilm-associated infections and plant diseases.

### V. Synergistic Applications: The Dual-Action potential.

The selenium nanoparticles (SeNPs) have proven to be an all-purpose nanomaterial in the agricultural industry, both its growth stimulators and protection systems. Their specific physicochemical traits allow them to be better in nutrient delivery, plant metabolism, and stress resilience, which makes them attractive candidates to be the next-generation nano-fertilizer and biostimulants. Besides enhancing the growth of plants, SeNPs have a high antimicrobial capacity, hence they can be used as eco-friendly nano-pesticides. SeNPs have the potential to control sustainable diseases and enhance crop production by direct inhibition of pathogens, stimulating plant defence mechanisms.

#### 5.1 Next-Generation Nano-fertilizers SeNPs and Biostimulants.

Selenium nanoparticles are nowadays considered as potential nano-fertilizers with the ability of enhancing the efficiency of nutrient use and the output of plants. SeNPs are used to make nutrient delivery and nutrient absorption by plant roots more

controlled due to their size in nanoscale and high surface reactivity (Qin et al., 2025).

It is demonstrated that the use of SeNPs can improve the growth parameters of plants: the increase of biomass, expansion of leaves, activity of antioxidant enzymes (Hasanuzzaman et al., 2020). These enhancements help in increased yield of crop and better health of plants. Moreover, fertilization by using SeNPs could be used to enhance selenium biofortification in agricultural plants and thus resolve the issue of selenium deficiency in populations (White, 2018).

#### 5.2 SeNPs in the roles of Eco-friendly Nano-pesticides and Disease Management Agents.

Selenium nanoparticles are antimicrobial agents and therefore they are explored to be environmentally friendly nano-pesticides. SeNPs have the capability to inhibit pathogens (bacteria and fungus) that cause crop diseases (Ikram et al., 2021). Besides direct antimicrobial effect, SeNPs have the capability to trigger plant defence and activate synthesis of protective secondary metabolites (Rastogi et al., 2019). Such effects increase plant resistance to attack of pathogens.

### VI. Toxicity, bio safety and Environmental Fate.

The use of selenium nanoparticles (SeNPs) in agricultural practices has elicited a lot of interest over its positive impacts on plant growth and ability to withstand stresses but their applicability has provoked some real questions on its toxicity, environmental fate, and biosafety. SeNPs have complex biological impacts and their effects are very much dose-dependent with the optimal concentrations associated with plant growth whereas excessive concentrations have been shown to cause phytotoxicity and metabolic disruptions. Moreover, after entering the soil, SeNPs become transformed, which determines their mobility and relation to soil microorganisms, which may impact nutrient-cycle and ecosystem stability. Thus, it is necessary to learn their effects in the environment and institute appropriate regulatory provisions to make the safe and sustainable utilization of selenium nanoparticles in agriculture.

#### 6.1 Dose Related Responses: The Point of Benefit and Phytotoxicity.

Even though selenium nanoparticles have numerous advantages in growth of plants, their biological effects are very dose-dependent. Low concentrations will lead to plant growth and stress

tolerance, but high concentrations can lead to phytotoxic effects (Hasanuzzaman et al., 2020). Selenium overload may affect the cell metabolism and cause plant tissue oxidation (White, 2018). This means that to make safe agricultural use, it is necessary to find out the optimal application concentrations.

### 6.2 Environmental Transportation and Effect on the Soil Microbiome.

After being applied to soil, selenium nanoparticles can be changed chemically e.g. through oxidation and aggregation. Through such mechanisms, the nanoparticles are affected in their movement and bioavailability in the soil environment (Ikram et al., 2021).

SeNPs are also capable of interplaying with soil microbial communities which are crucial in the nutrient cycling as well as plant well-being. Middle levels can cause the stimulation of the positive microorganisms, and excessive levels can cause disturbance in the microbial diversity (Rastogi et al., 2019).

### 6.3 Biosafety and Regulatory Issues to be Applied.

The booming DNA technology in agriculture has brought critical regulatory and bio safety issues. Risk assessment structures are needed to determine the environmental and health effects of agricultural products that contain nanoparticles (Kah et al., 2018).

Regulatory bodies insist that such things as standardized tests of toxicity, environmental surveillance, and life-cycle analysis should be carried out prior to deployment of nanomaterials in agriculture in large scale (Mukhopadhyay et al., 2014).

## VII. Summary of Key Findings

SeNPs can be considered as the potential useful nanomaterial with great potential in agriculture and plant biotechnology. Their small size in nanoscale, large surface area and increased reactivity enable them to react effectively with plant tissues and microbial cells, among other functional advantages (Ikram et al., 2021). Research articles that were under consideration in this work confirm that SeNPs are capable of supporting the growth of plants and their physiological functioning by promoting nutrient absorption, arousing the antioxidant defence system and controlling metabolism related to the growth of plants (Hasanuzzaman et al., 2020).

Other than acting as promoters of plant growth, selenium nanoparticles are also known to

have high antimicrobial potential against a broad spectrum of plant pathogenic microorganisms. These antimicrobial actions are the result of several processes such as membrane disruptive effect, the creation of oxidative stress, and disruption of microbial metabolic conditions (Menon et al., 2022). Therefore, SeNPs also have the potential to act as plant developmental stimulants as well as antimicrobial agents, which points to their dual-sided activity in enhancing crop growth and nutrition of plants.

Also, SeNPs were shown to reduce abiotic stresses, including drought, salinity, and heavy metal toxicity, and to improve plant antioxidant protection and cellular redox balance (White, 2018). These characteristics pose that selenium nanoparticles can be useful as nano-fertilizers and environmentally friendly agent of protection of plants in sustainable farming systems.

### 7.1 Literature Knowledge Gaps and Limitations of the Current Study.

Although selenium nanoparticles have been shown to have promising applications in agriculture, there still exist several areas of limitations and knowledge gaps that have to be addressed before these applications can be adopted in agriculture. The root cause of one of the challenges is the low level of knowledge on the uptake pathways and transformation of nanoparticles in plant tissues. Despite the evidence of root uptake and translocation of the SeNPs, the exact action and transport of these nanoparticles as well as how they are metabolized in the plant is poorly comprehended (Gupta and Gupta, 2017).

The other limitation is related to the differing conditions of the experiment among the existing research works. Nanoparticles vary in the way they are synthesized, size, concentration, and so to come by plant species causing inconsistency between experiments (Ikram et al., 2021). This inconsistency complicates the creation of universal rules to use SeNP in agriculture systems.

There are also issues that surround the long-term environmental and ecological consequences of the use of nanoparticle. Although divergent doses of SeNPs have the potential to positively influence plant development, exposures to large doses might affect soil microbial communities or become trapped in food chains (Kah et al., 2018). Hence, to determine the environmental safety and sustainability of Agricultural technologies using SeNPs, extensive studies on the risks should be conducted.

## 7.2 Future Future directions of Field-scale application and commercial translation.

The research needs to be widened in future since there is a gap that still lies between laboratory scale research and field scale applications of selenium nanoparticles. Majority of the studies that have been carried out are under controlled experimental settings, which might be not representative of the complexity of actual agricultural settings (Rastogi et al., 2019). Mass field experiments are thus needed to determine the effectiveness, stability and cost-effectiveness of SeNP-based plant protection agents and fertilizers.

The other key research area is production of greener synthesis procedures of selenium nanoparticles. Plant extracts, microorganisms and other biological systems were also shown to be less environmentally harmful and superior in developing green synthesis approaches because they are more sustainable (Ikram et al., 2021). Additional optimization of the suggested synthesis techniques would help to manufacture stable and biocompatible SeNPs formulations that can be used in agriculture.

Moreover, nanotechnologists, regulatory authorities, and plant scientists will be required in an interdisciplinary partnership in order to translate laboratory findings to commercial products. Setting up the standard of the application protocols, security standards, and legal frameworks will be essential in making sure that SeNP-based technologies in Agriculture are used responsibly (Kah et al., 2018). On the basis of future study and technological progress, selenium nanoparticles can become essential elements of the nano-agriculture system of the next generation that will be developed with this purpose the enhancement of crop productivity and environmental sustainability.

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