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Green synthesis of mono and bimetallic selenium nanoparticles and their applications in biomedical and agriculture

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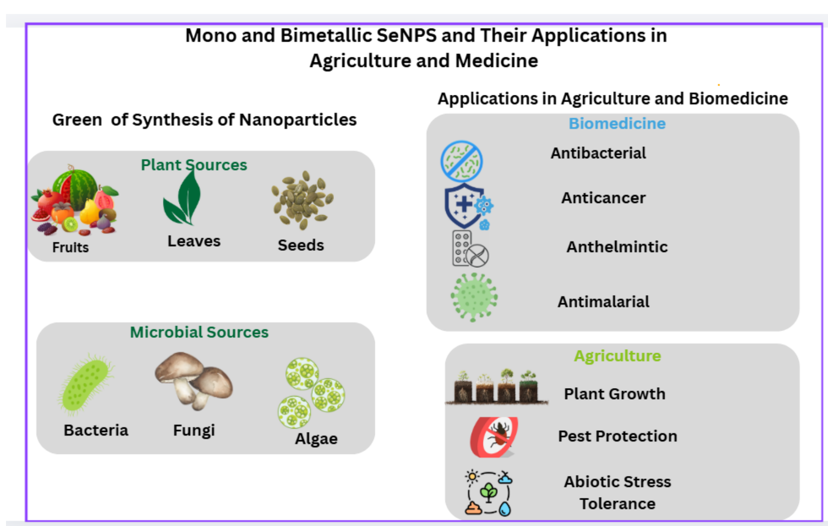
ABSTRACT: The need for more effective and environmentally sustainable solutions to various medical and agricultural issues in the current scenario has driven significant interest in nanomaterials, among which selenium nanoparticles (SeNPs) have emerged as particularly promising. The current review discusses the role of mono and bimetallic selenium nanoparticles and their applications in agricultural and biomedical studies. An overview of different plant and microbial sources available for green synthesis of nanoparticles is highlighted. Silver, gold, zinc, and selenium nanoparticles and their general characteristics are presented briefly. The phytochemicals generally involved in the green synthesis of metal nanoparticles are discussed. The literature review of the synthesis of mono and di-selenium nanoparticles using various plants and microbial sources is reported. Applications of selenium nanoparticles in the biomedical field as antibacterial, antifungal, anticancer, antimalarial, anthelmintic and wound healing agent are discussed. The role of selenium nanoparticles in agriculture for plant growth, protection against pests and abiotic stress is outlined.

GRAPHICAL ABSTRACT



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1. Introduction

Nanoparticles are materials that vary in size from one to a hundred nanometres. They have distinct physical, chemical, and biological characteristics because of their small size. These characteristics include increased reactivity, surface area and quantum phenomena. Nanoparticles are a major focus of nanotechnology research and applications because of their applications in medicine, electronics, energy, and environmental science (Baig et al., 2021).

Metal nanoparticles are extensively explored for their electrical, optical, catalytic, and antimicrobial properties. Common metal nanoparticles such as gold, silver, platinum, and iron have attracted considerable research interest due to their stability, biocompatibility, and ease of functionalization (Burlec et al., 2023). Metal nanoparticles are synthesized by two methods, the top-down and bottom-up approaches. They can be synthesized chemically, physically or biologically. Physicochemical methods are often associated with toxicity, high energy demands, and environmental hazards, raising concerns about environmental and biological safety. Therefore, green synthesis using biological agents such as plant and microbial extracts is considered a safer alternative (Saxena et al., 2025). The following figure shows the sources for green synthesis.

Several parts of plants, such as leaves, flowers, fruit, seeds, bark, and roots, are used to synthesize the nanoparticles. In microbes, bacteria, fungi, algae, yeast, and viruses are used to synthesize the nanoparticles (Chan et al., 2022). The following table shows the various sources of plants and their parts used for the synthesis of nanoparticles.

Carbohydrates, amines, alkaloids, polyphenols, anthocyanins, saponins, steroids, tannins, and enzymes from plants and microorganisms act not only as reducing agents but also as capping or stabilizing agents (Gour & Jain, 2019). The following figure shows the various biochemicals that play a significant role in the synthesis of metal nanoparticles.

Reducing sugars and alkaloids are good reducing agents that donate electrons to metal ions for reduction to metal nanoparticles (El-Saadony et al. 2025). Protonated amines interact with negatively charged microbial membranes, causing membrane disruption (Dankar et al., 2025). Polyphenols are strong antioxidants which neutralize free radicals that prevent ROS generation. Anthocyanins are natural pigments that act as antioxidants that stabilize free radicals via resonance.

Table 1.
Plant-parts and their phytochemicals used in nanoparticles synthesis.

Plant Part	Source	Biomolecules	Reference
Leaves	Guava	Flavonoids, Ascorbic acid	(Islam *et al.*, 2024)
Roots	Garlic	Allicin, Selenium-containing compounds	(Aftab *et al.*, 2023)
Bark	Cinnamon	Polyphenols	(Alghuthaymi *et al.*, 2021)
Fruits	Gooseberry	Flavonoids, Ascorbic acid	(Gunti, Dass and Kalagatur, 2019)
Seeds	Ajwain	Tannins, saponins, flavanoids	(Qamar, John and Bhatti, 2020)
Flowers	Marigold	Cowmarin, glycosides, terpenoids	(Hernández-Díaz *et al.*, 2021)
Peel	Orange	Polyphenols, Carotenoids, flavonoids	(M. F. Salem *et al.*, 2022)
Pulp	Pomegranate	Ellagitannins, Flavonoids, anthocyanins	(Hashem, Saied, *et al.*, 2023)

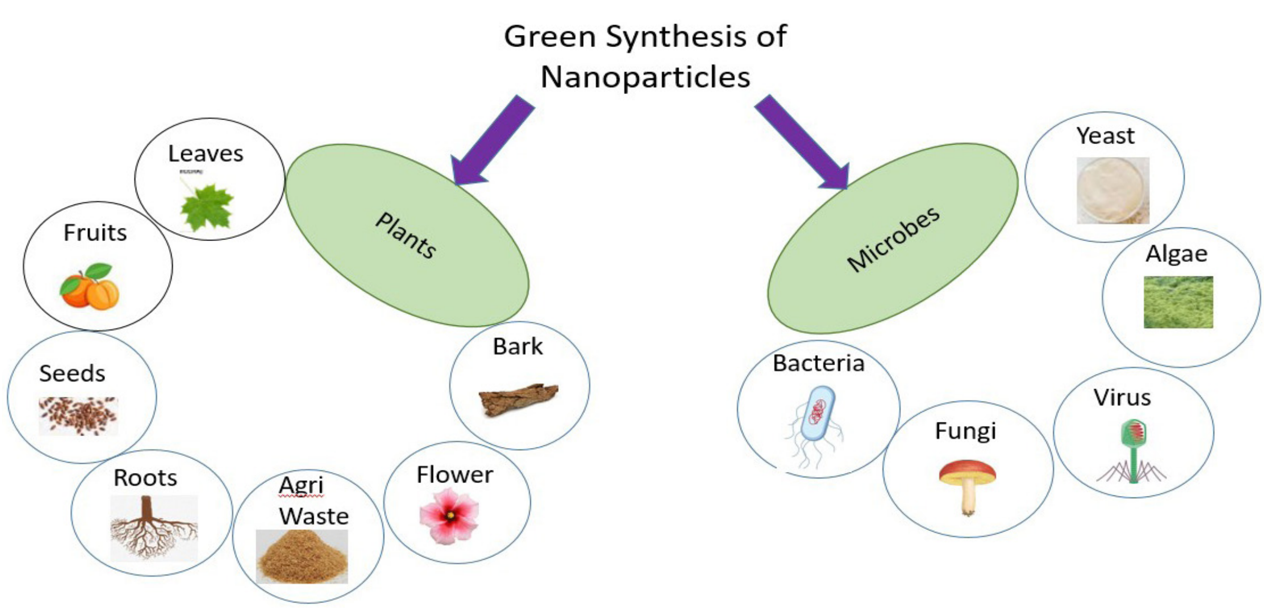

Figure 1. Green synthesis using Plants and Microbes.

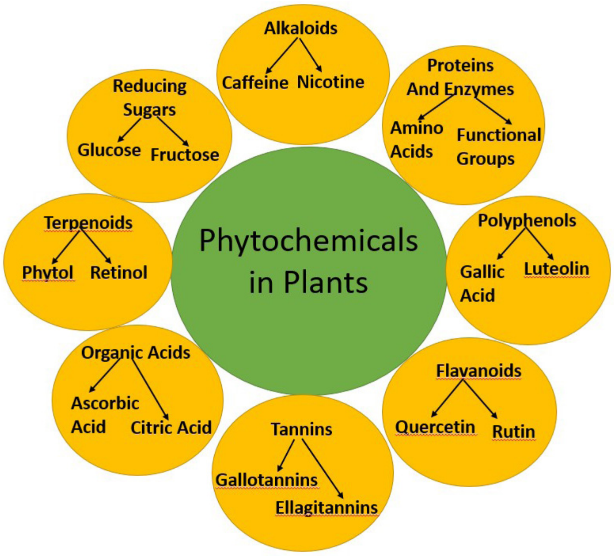

Figure 2. Phytochemicals in the synthesis and stabilization of nanoparticles

Saponins bind sterols in the cell membranes of microbes to form pores that lead to cell lysis. Due to their rigid polycyclic structure, steroids limit uncontrolled nanoparticle growth by capping, thereby influencing nucleation and growth kinetics. Tannins scavenge free radicals through phenolic groups and prevent ROS generation. Enzymes help in the hydrolysis of glycosidic linkages of cell walls that allow metals to enter the microbe and help in the synthesis of nanoparticles (El-Seedi et al., 2024).

2. Categories of Nanoparticles

2.1. Metallic nanoparticles

Owing to their remarkable optical, electrical, and magnetic properties, metallic nanoparticles are used extensively in the field of scientific research. Among the various metallic nanoparticles, silver, gold, copper, and zinc nanoparticles are studied extensively due to their relative inertness, stability, biocompatibility, and wide applications (El-Seedi et al., 2024). Currently, selenium is emerging as a potential metal for nanoparticles due to their optical, electrical, photochemical, and antimicrobial properties (Mikhailova, 2023).

2.2. Silver nanoparticles

Due to its high electrical and thermal conductivity and antimicrobial properties, silver has wide applications ranging from electronics, medicine, solar technology, water purification, and so on. Since silver is one of the oldest known metals used for its antimicrobial activity, several studies have been reported for its role as an anticancer and burn and wound healing agent (Babu et al., 2024; Rao et al., 2016). Silver nanoparticles (AgNPs) are also used in the textile industry, food packaging industry and purification of water (Lekha et al., 2021).

Since the discovery of nanotechnology, AgNPs have been synthesized by the reduction of silver ions (Ag^+) into elemental silver (Ag^o) by physical and chemical methods. The disadvantages of the physical and chemical synthesis of nanomaterials led to green synthesis of AgNPs, where plants, bacteria, fungi, yeast, and algae extracts are used in the synthesis of AgNPs (Chakravarty et al., 2022; Dakal et al., 2016). Biomolecules such as reducing sugars, phenolic acids, amino acids, enzymes and proteins present in plants and microbes are involved in the conversion of metal salts to their nanoparticles. Different factors such as pH, concentration of metal ion solution, temperature and concentration of extract were found to affect the size and shape of AgNPs (Nie et al., 2023). The cytotoxicity of nanoparticles has been attributed to the fact that since metal nanoparticles have the same dimension as that of microbes, they can penetrate the microbial cell membrane by damaging it and ultimately destroy the microbe through various complex mechanisms, which can include reactive oxygen species (ROS) generation, DNA damage and induced cell apoptosis. (Amr et al., 2023; Rao et al., 2016; Rodrigues et al., 2024).

2.3. Gold nanoparticles

Gold nanoparticles are one of the most extensively synthesized nanoparticles due to their stability, biocompatibility, ease of functionalization or size-tunability, and relatively less toxicity due to their inertness. Since the applications of AuNPs significantly depend on the size and shape of nanoparticles, different shapes of AuNPs have been explored, such as gold nanorods, nanospheres, nanotriangles, nanostars, and nanocages (Georgeous et al., 2024). The ability to interact with light via surface plasma resonance makes them useful in medical imaging techniques, cancer therapy, and drug delivery (Karnwal et al., 2024). The optical property of gold nanorods has enabled scientists to apply them to burn cancer cells with the heat generated in the process. Since this process has no significant side effects when compared to regular radiation or chemotherapy, it can be considered more advantageous (Santhosh et al., 2022)

Gold nanoparticles get easily attached to proteins, enzymes, nucleic acids, and drugs due to their enhanced surface charge and size. This surface-functionalization also prevents the aggregation process of nanoparticles and gives extra stability to the nanoparticles. These NPs are widely used in therapeutics, imaging, detection, and surface alteration with drugs, antibodies, or polymers for specific applications (Amina & Guo, 2020). AuNPs are used in Raman scattering, photodynamic therapy, radiation therapy, biosensors, and computed tomography for therapeutic, diagnostic, and biomedical imaging applications (Bansal et al., 2020). AuNPs are used in biological assays for qualitative and quantitative analyses of proteins, which are applied for the investigation of kidney disorders, heart diseases, and cancer. AuNPs affect seed germination, node elongation, enhance chlorophyll content, and improve vegetative growth of plants (Hammami et al., 2021)

2.4. Zinc nanoparticles

Zinc is an essential element vital for life, required for growth and metabolism, as it supports the function of over 300 enzymes involved in various metabolic processes. It also plays a key role in cell division and the synthesis of proteins and DNA, which are crucial in the cellular defence mechanism. In humans, zinc is found in bones, tissues, and muscles (Pushpalatha et al., 2022). Due to its unique optical, electrical, electronic, and magnetic properties, zinc occupies a special place in the study of nanoparticles. Zinc nanoparticles can be prepared in various shapes such as nanotubes, nanorods, nanosheets, nanohelixes, nanorings, nanoribbons, nanobelts, nanosprings, nanoneedles, nanowires, nanocombs, nanopellets, flowers, coniferous urchin-like structures, dandelions, and snowflakes (Raha & Ahmaruzzaman, 2022).

Due to its large band gap, it is applied in energy harvesting, light-emitting diodes and solar cells. Due to its antimicrobial, anti-inflammatory, and anticancer activities, it is used for treating wound healing, eczema, hemorrhoids, and cancer. In agriculture, it is applied for plant growth and an antistress role (Singh et al., 2018). It is used as a photocatalytic agent to tackle organic contaminants in wastewater. Zinc oxide nanocomposites with various metal or metal oxides, such as aluminium and silicon, have been used for sensing of gases such as NO_2 and CO. ZnONPs have been used for making self-cleaning, water-repellent and ultraviolet-blocking textiles. Zinc is preferred by many researchers over silver and gold as it is less expensive and can exhibit almost the same properties as these two metals (Raha & Ahmaruzzaman, 2022).

2.5. Selenium nanoparticles

Selenium is an essential trace element required for the normal functioning of the immune systems in humans, plants and animals. Since selenium is relatively abundant in the earth's crust, it is taken up by plants as inorganic salts, selenates, and selenites, thus entering the food chain. In biological systems, they form selenocysteine and are involved in the formation of many selenoproteins (Rayman, 2020). Selenoproteins are involved in reproduction, hormone metabolism, DNA synthesis, and prevention of oxidative stress and cell death (Medina Serrano et al., 2020).

Selenium stands out among trace elements due to its narrow range between toxicity and deficiency. Since elemental selenium is the least toxic form of selenium compared to its salts, its nanoform has attracted significant attention (Bhattacharjee et al., 2019). Functionalized SeNPs exhibit less cytotoxicity than their other forms, such as selenate, selenite, selenoproteins, and inorganic selenium (Hu et al., 2023). Since SeNPs show promising potential as antioxidants, anticancer agents, and drug carriers in biomedical applications, several studies have supported their anticancer, antioxidant, antimicrobial, and antibiofilm properties. SeNPs were found to possess semiconducting, photoelectric and X-ray-sensing properties and therefore are used in photocells, photocopying, photometers, and xerography (Bisht et al., 2022). Selenium is preferred for nanoparticle synthesis due to its diverse roles in biological systems and wide applications as an antioxidant, antimicrobial, and anticancer agent, as well as for improving crop stress tolerance in agriculture (Medina Serrano et al., 2020).

2.5.1. Mono and bimetallic selenium nanoparticles

The green synthesis methods discussed above can be applied to synthesize various forms of selenium nanoparticles:

1. Monometallic SeNPs: These are pure selenium nanoparticles.
2. Bimetallic SeNPs: These involve selenium combined with one other metal, such as zinc or cadmium, potentially enhancing their properties and applications.

3. Green Synthesis of Monometallic SeNPs

SeNPs obtained using the aqueous extracts of *Ceropegia bulbosa* tubers were found to be active against cancer cells, pathogens, and mosquito larvae. The particles also showed significant photocatalytic degradation of dye (Cittrarasu et al., 2021). Salem et al. synthesized 16–95 nm-sized SeNPs from orange peel waste and studied their antibacterial and antibiofilm activities. It was found that SeNPs were most active against *Streptococcus aureus* compared with *Pseudomonas aeruginosa, Escherichia coli* and *Klebsiella pneumonia* (Salem et al., 2022b). SeNPs synthesized using pomegranate peel extract were studied as an edible antifungal agent on citrus fruits and found to be better agents to tackle the issue of fungal attack on citrus fruits (Salem et al., 2022a). *Amphipterygium glaucum* leaves (AGL) and *Calendula officinalis* flowers (COF) were used for the synthesis of SeNPs, and their antifungal activity against *Fusarium oxysporum* and *Colletotrichum gloeosporioides* was studied. It was observed that the AGL extract was better as an antifungal agent because of its size (8 nm) compared to COF because of its bigger size (134 nm) (Lazcano-Ramírez et al., 2023).

Researchers synthesized SeNPs using *Allamanda cathartica* L flower extract and observed the promotion of mustard growth under salt stress. The synthesized nanoparticles were found to enhance germination by 31%, root length by 78%, shoot length by 92% and chlorophyll content by 49% with 200 mM NaCl stress. The study reports optimization of pH, extract concentration, concentration of SeO_2 and time for completion. Best results were obtained when 30% flower extract was used to reduce a 35 mM solution of SeO_2 at pH 4 for 6 h (Sarkar & Kalita, 2022). Another research by a group of scientists showed that SeNPs were synthesized using propolis extract by six different methods, namely, hydrothermal, microwave irradiation, ultrasonication, UV radiation, self-assembling, and conventional heating. The study shows antioxidant activity, turbidity, pH, and brix values of the provided hydroalcoholic propolis extract were 85.8%, 2.235% a.u., 4.1, and 3.2°Bx, respectively (Hatami et al., 2020). Vasylchenko and Derevianko (2021) determined the antifungal properties of SeNPs and iodine NPs and observed that this mixture of NPs inhibited the growth of *Acremonium cucurbitacearum, Acremonium strictum*, and *Fusarium* species. SeNPs synthesized using *Trachyspermum ammi* seed extract were used to study the toxicological and therapeutic effects in arthritic mice. The particles showed significant results in the redox state of the inflamed synovium. This was attributed to the activity of antioxidant enzymes in comparison to the controls (Qamar et al., 2020)

Bacillus megaterium extract-based synthesis of Se-NPs of size 41.2 nm was studied and found to exhibit antifungal activity against *R. solani in vitro*. SeNPs were able to alleviate the effect of *R. solani* damping-off and minimize root-rot disease with the soaking and spraying method (Hashem et al., 2021). Dhanraj and Rajeshkumar (2021) synthesized SeNPs from *Brassica oleracea* and found them to be effective against *Streptococcus mutans, S. aureus, Enterococcus faecalis, Lactobacillus*, and *Candida albicans*, which are common cavity-causing bacteria. SeNPs using a blue–green microalgae, *Spirulina platensis*, were synthesized at pH 5 using light and darkness, and their antioxidant property was studied (Alipour et al., 2021). *Diospyros montana* (DM) bark extract was used to synthesize SeNPs, and its antioxidant property and antimicrobial and anticancer activities were studied. The particles showed significant antimicrobial activity against *Bacillus subtilis* and *E. coli* and significant antiproliferative activity against the cancerous cells. Cells treated with DM-SeNPs showed reduced cell viability, loss of cell-to-cell contact, cell shrinkage, and formation of apoptotic bodies (Puri & Patil, 2022).

Se-NPs were synthesized using the fungal strain, *Penicillium crustosum*. The particles showed significant antimicrobial, anticancer activity and photodegradation of dyes. The particles exhibited excellent stability and reusability without loss of activity for the degradation of dyes. This study showed that antimicrobial, anticancer and catalytic activity of Se-NPs were enhanced by the presence of light (Fouda et al., 2022). *C. officinalis* was used to synthesize SeNPs, where ascorbic acid was used as a reducing agent, and the flowers and stem or leaf extracts with different solvents were used as stabilizing agents. The antioxidant and antimicrobial study showed that the methanolic extract was moderately active against the bacterial strains at different time periods (Hernández-Díaz et al., 2021). The leaf extract of Tarragon, *Artemisia dracuncu*, was used along with ascorbic acid as stabilizing and reducing agents, respectively, to synthesize SeNPs. The particles exhibited significant antibacterial and antifungal activity as the SeNPs cross the cellular membrane of the bacteria by creating

Table 2.
Monometallic SeNPs from different plant and microbial source and their applications.

Source	Name of species	Applications	Reference
Flower	*Cassia javanica*	Antibacterial, antioxidant, biomedical and agricultural applications	(Zhao et al., 2024)
Leaf	Aloe vera	Antimicrobial, antioxidant, anticancer activity	(Menon et al., 2021)
Bark	*Terminalia arjuna*	Antioxidant, anti-inflammatory and biomedical applications	(Gunti et al., 2021)
Bacteria	*Halomonas elongata & Salinicoccus iranensis*	Biocompatible SeNPs, antimicrobial and antioxidant activity	(Tabibi et al., 2023)
Bacteria	*Bacillus cereus*	Environmental remediation, antimicrobial applications	(Dhanjal & Cameotra, 2020)
Fungi	*Aspergillus terreus*	Antimicrobial, antioxidant and biomedical applications	(Fesharaki et al., 2020)
Fungi	*Penicillium chrysogenum*	Antimicrobial, antioxidant and biomedical applications	(Al-Shabib et al., 2021)
Yeast	*Saccharomyces cerevisiae*	Antioxidant, nutraceutical and biomedical applications	(Eszenyi et al., 2021)
Algae	*Spirulina platensis*	Antioxidant, antimicrobial and food-related applications	(El-Seedi et al., 2024)
Algae	*Chlorella vulgaris*	Biomedical, antioxidant and environmental applications	(El-Sheekh et al., 2022)

an osmotic imbalance and breaking bonds in the biochemical matrix. After entering the cell, the particles might be involved in the generation of reactive oxygen species, which could directly impact or begin a cascade of biochemical processes that eventually lead to the death of the bacterial cell. Similarly, the fungal plasma membrane seems to be ruptured by the reactive oxygen or free radicals generated by SeNPs. The particles could be inhibiting the generation of spores and growth of mycelia by blocking glutathione activity, which eventually leads to apoptosis (Yilmaz et al., 2021).

Solanum lycopersicum (tomato) fruit and seed extracts were used to synthesize the SeNPs using different concentrations of salt and extracts, pH, time, and temperature. The particles exhibited significant antioxidant, antibacterial, and antidiabetic activities (Sani-e-Zahra et al., 2022). SeNPs obtained from orange fruit peel extract were studied for their microbial activity against *Staphylococcus aureus*, which was found to be significant (Dang-Bao et al., 2022). Four different fungal species were used to synthesize 25–75 nm-sized SeNPs after incubation for 24 h. Among the four, *Penicillium verhagenii* was found to be the best for synthesis of nanoparticles. The antibacterial, antioxidant, cytotoxicity, and larvicidal activities were determined and found to be significant (Nassar et al., 2023).

Bacillus paranthracis and *E. ludwigi* were used to synthesize SeNPs, and it was observed that the former gave rod-like SeNPs on the edge of the bacterial cell, as seen by TEM images. The cell wall of *B. paranthracis* was better than that of *E. ludwigi*, which is attributed to the fact that Gram-positive bacteria are surrounded by layers of peptidoglycan many times thicker than those found in Gram-negative bacteria. The bacterial strains from habitats with selenium abundance were more efficient in reducing the salt of selenium than those from a Se-free environment, which substantiated the fact that different bacterial strains reduced the salt solution to different extents. The observance of garlic-like odor during the appearance of red coloration authenticated the production of volatile methylated Se products. It was suggested that the cell wall of the microorganisms plays a significant role in the synthesis of SeNPs. They noticed that the sticking of nanoparticles to the cell wall agrees with the Derjaguin–Landau–Verwey–Overbeek (DLVO) theory (Sans-Serramitjana et al., 2023a).

The effect of ascorbic acid-reduced SeNPs on rice germinating seeds was observed extensively. According to them, low concentration of SeNPs did not affect the seedling-growth, but there was increased antioxidant enzyme activities and ROS scavenging with higher concentrations of the particles, strong inhibition of seedling growth, and decrease in antioxidant enzyme activity, proving a direct relationship between concentration of SeNPs and its toxicity (Freire et al., 2024).

Hibiscus sabdariffa extract made from its leaves was used to synthesize SeNPs by reducing selenious acid. The particles were analyzed for antioxidant and anti-diabetic activity in rats. The decrease in testosterone caused by streptozotocin-induced diabetes was found to be enhanced by the SeNPs. This was attributed to the action of nanoparticles causing reduction of nitric oxide and lipid peroxidation. It was also observed that SeNPs increased the activities of antioxidant enzymes and glutathione content in testicular tissues and also prevented the histological damage occurring in the testes of streptozotocin-induced diabetic rats (Fan et al., 2020). *Abelmoschus esculentus* extract was used to synthesize SeNPs and studied for their antibacterial activity against Gram-positive and Gram-negative bacteria. The particles were more efficient against Gram-positive bacteria due to the high negative charge, peptidoglycan layer, and purines (Ghaderi et al., 2022).

Researchers have synthesized SeNPs with starch as the stabilizing agent and glucose and ascorbic acid as reducing agents separately and observed that addition of starch to sodium selenite and incubating at 80 °C did not change the color of salt solution significantly even after 48 h, but the addition of glucose and ascorbic acid changed the color to dark red within 7 and 4 h, respectively, proving that starch is acting only as stabilizing agent and not as reducing agent and ascorbic acid is a better reducing agent than glucose. The study observed the photocatalytic activity, antimicrobial and cytotoxicity of the synthesized nanoparticles, and the results were satisfactory (Kazemi et al., 2021)

SeNPs were synthesized using *Vitis vinifera L* (raisin) and were used to study their effect on seed germination in rice as a seed nanopriming agent. The terpenoid, phenol, saponin, steroid, flavonoid, alkaloid, tannin, reducing sugar, soluble carbohydrate, protein, and antioxidant contents in raisins were analyzed by standard methods. Germination test, Seed imbibition, biochemical assay, seedling vigor and enzyme activities were analyzed. Seed germination rate, starch mobilization, embryo viability, seedling vigor, ROS extent in rice seeds, and antioxidant enzyme activity in seeds undergoing germination were observed using standard methods and observed to be encouraging (Setty et al., 2023)

3.1. Bimetallic SeNPs

Cadmium Selenide (CdSe) and zinc selenide (ZnSe) were prepared separately, and CdSe/ZnSe composite was prepared in aqueous solution with L-cystine and Cetyltrimethylammonium bromide (CTAB) solvents as capping agents to form the particles as nanorods. CdSeNPs were synthesized using cadmium nitrate, sodium selenite and hydrazine hydrate in an ammoniacal medium as a reducing agent. ZnSeNPs were synthesized using zinc nitrate, sodium selenite and hydrazine hydrate. The composite CdSe/ZnSe nanocrystals were obtained by mixing CdSe in L-cysteine and ZnSe in CTAB and autoclaving at 200 °C for 4 h. The characterization of the prepared composite particle and its photoluminescence study showed that the quality and morphology of the crystals were better due to the surface functionalization and composting of the particles. Luminescence and quantum yield of the particles are compared, which proves that CdSeNPs have better band edge and quantum yield than ZnSeNPs (Ramalingam, 2016). Table 3 provides the information related to the bimetallic selenium nanoparticles from different sources and their applications.

Zinc oxide nanoparticles doped with selenium were synthesized using *Mangifera indica* leaf extracts by adding zinc acetate to sodium selenite and plant extract, and stirring for an hour at ambient temperature. The particles were studied for their photo degradation and antibacterial studies and found to be effective enough (Dhivya et al., 2019). AgNPs capped with Selenium were synthesized using *Ocimum tenuiflorum* extract. The role of extract and temperature on the size of the synthesized particles was explored. The phytochemicals present in the extract acting as reducing agents were established using gas chromatography-mass spectrometry. The possibility of genotoxicity was analyzed using molecular docking studies and proved to be negligible in low concentrations. Cytotoxicity and antioxidant property were also observed (Olawale et al., 2021). Amit et al. synthesized SeAgNPs using an equimolar mixture of gallic acid and quercetin and studied their antimicrobial, antioxidant, and anticancer effects. Interestingly, they found that neither quercetin nor gallic acid was able to reduce the metal salt solutions individually (Mittal et al., 2014)

Researchers synthesized AgSeNps using watermelon rind extract, and their antimicrobial, anticancer, and cytotoxicity studies were conducted. The bimetallic particles showed significant anticancer activity toward the cancerous cell line (Hashem et al., 2023). Hamida and coworkers synthesized AgSeNps from *Orobanche aegyptiaca* and studied its antimicrobial and antibiofilm activities along with bacterial membrane permeability mechanism, kinetic study and effect of UV exposure. They found that even at low concentrations, the particles showed good efficiency (Mostafa et al., 2023). Researchers synthesized ZnSeNPs from *Gracilaria corticata* extract and studied their antioxidant, antimicrobial, biofilm inhibition assay, and antitumor assay. The particles showed good efficiency in all the activities (Mirzaei et al., 2021). Aly Khalil et al. (2024) synthesized SeAuNPs using *Pluchea indica* extract and observed their antibacterial and anticancer activity.

4. Applications of Selenium Nanoparticles

As mentioned earlier, selenium nanoparticles have been used in various fields, such as biomedical, electronics and sensing, food industry, environmental, material science, energy storage and conservation, therapeutic and diagnostic applications, and agricultural applications. In this review, their role in biomedical, agricultural, and environmental applications is discussed. The Figure 3 below outlines the applications of selenium in a few such important fields.

4.1. Selenium nanoparticles and their biomedical applications

As a component of glutathione peroxidase and thioredoxin reductase, selenium helps protect cells from

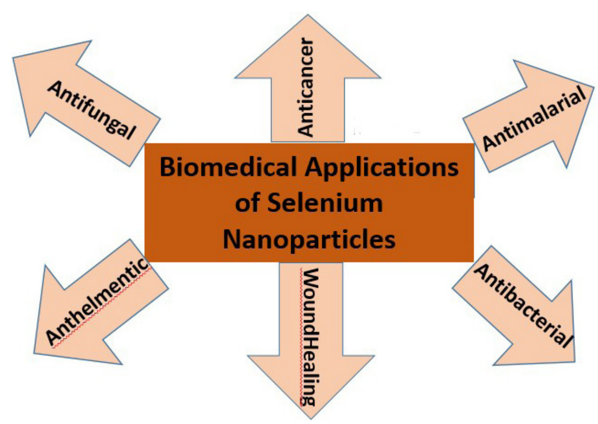

Figure 3. Biomedical applications of Selenium nanoparticles

Table 3.
Bimetalic SeNPs from different sources and their applications.

Source	Species	Bimetallic composition	Applications	Reference
Bacteria	*Bacillus paramycoides*	Ag–Se	Antimicrobial, antibiofilm, antioxidant, photocatalytic (dye degradation)	(El-Behery et al., 2023)
Leaf	*Pluchea indica*	Se–Au	Antibacterial & anticancer activities	(Afshari et al. 2023)
Algae	*Padina boergesenii*	Se–ZnO	Anticancer	(Balaji et al., 2024)
Seed	*Vitis vinifera*	Se/ZnO	Antibacterial, antioxidant, cytotoxicity & plant biostimulant properties	(Selim et al ., 2025)
Leaf	*Lagenaria siceraria*	CuO–Se	Antibacterial, anticancer	(Elkady et al., 2025)

oxidative stress and supports immune function, thyroid hormone metabolism, and DNA synthesis. Growing interest of the scientific community aimed at the therapeutic potential of selenium, which includes health management, including cardiovascular diseases, cancer, neurological diseases, thyroid dysfunction, and viral infections. The following Table 4 outlines the emerging evidence on selenium's therapeutic roles, examining its mechanisms of action and evaluating its impact across various clinical and pathological conditions.

4.1.1. Antibacterial property

SeNPs have shown prominent antibiotic activity against bacteria, fungi, and viruses. SeNPs have shown efficacy against both Gram-positive and Gram-negative bacteria (Bisht et al., 2022; Sans-Serramitjana et al., 2023b). The mechanism of action involves disruption of bacterial cell membranes, generation of reactive oxygen species (ROS) and interference with bacterial metabolic pathways. Studies have shown the impact of SeNPs against antibiotic-resistant strains, suggesting their possibility as a substitute for the antibiotics currently in use (Ridha et al., 2024).

4.1.2. Antifungal activity

SeNPs exhibit potent antifungal properties, particularly against opportunistic fungal pathogens. Their mechanism includes inhibition of fungal growth, disruption of fungal biofilm formation, formation of ROS, suppression of certain enzymes or interference with mitochondrial function, when combined with conventional antifungal drugs (EL-Sayed et al., 2024; Lazcano-Ramírez et al., 2023). Studies have shown antifungal activity of SeNPs against *C. albicans* (Rostamzadeh et al., 2024). *F. oxysporum* and *Colletotrichum gloeosporioides* (Lazcano-Ramírez et al., 2023). However, toxicity at high concentration, lack of standardization in nanoparticle synthesis and limited *in vivo* studies are considered as the disadvantages in scaling up selenium nanoparticles as a commercial antifungal product.

4.1.3. Anticancer properties

SeNPs have shown promising results in cancer therapy, demonstrating both preventive and therapeutic effects (Menon et al., 2018). The anticancer effect of SeNPs is attributed to several processes, such as induction of cell death in cancer cells, arrest of cell division, inhibition of angiogenesis, selective production of ROS in malignant cells, and modulation of cell signaling pathways. SeNPs have shown efficacy against cancer cells of the breast, prostate, colorectal, lung, and liver. SeNPs are being investigated as potential carriers for site-specific drug transport in cancer therapy, offering enhanced drug stability, improved cellular uptake and controlled side effects (Othman et al., 2022).

4.1.4. Antimalarial properties

SeNPs show promising antimalarial properties, primarily by acting as broad-spectrum antimicrobial and immunomodulatory agents that can target malaria parasites and help improve overall infection outcome (Husain et al., 2025). The antimalarial activity of SeNPs is attributed to inhibition of parasite growth, disruption of the parasite's life cycle, and alteration of the host's defence mechanism (Salem et al., 2021). SeNPs have shown promise in combating drug-resistant strains of malaria parasites, suggesting their potential as novel antimalarial agents (Yazhiniprabha & Vaseeharan, 2019).

4.1.5. Anthelmintic properties

Selenium nanoparticles have demonstrated efficacy against various helminth parasites, showing potential as alternative anthelmintic agents. The anthelmintic activity of SeNPs involves direct toxicity to adult worms and larvae, inhibition of egg hatching, and disruption of the parasite's

Table 4.
Applications of selenium nanoparticles in biomedical field and their mechanism of action.

Activity	Application	Mechanism of action	Ref
Anticancer Agent	Selenium nanoparticles have shown cytotoxic effects against various cancer cells.	Induction of apoptosis, modulation of signaling pathways.	(Medina-Cruz et al., 2023)
Antibacterial Agent	Active against a wide spectrum of bacteria, including multi-resistant organisms.	Disruption of bacterial membranes, production of ROS.	(Karthik et al., 2024)
Antifungal Agent		Demonstrated efficacy against several fungal pathogens (Lazcano-Ramírez et al., 2023)	
Antimalarial and Antiparasitic Agent	Potential in treating malaria by targeting the plasmodium parasite	Induction of oxidative stress within the parasite.	(Sharma, Rawat and Bohidar, 2023) (Arafa et al., 2023)
Anthelmintic	Broad spectrum anthelmintic potential	Helminthiasis	(Kaiaty et al., 2023)
Neuroprotection	Shows improvement in Alzeihmers Disease.	Preventing cellular degeneration.	(Vicente-Zurdo, Rosales-Conrado and León-González, 2024)

biochemical pathway (Kaiaty et al., 2023). Research has indicated the effectiveness of SeNPs against both intestinal and tissue-dwelling helminths, highlighting their broad-spectrum anthelmintic potential (Sarhan et al., 2022). While selenium nanoparticles show great promise in various medical applications, several challenges need to be addressed, such as optimization of synthesis methods for consistent size and shape, understanding the long-term effects and potential toxicity, development of targeted delivery systems, and regulatory approval for clinical use.

4.1.6. Wound healing properties

SeNPs show encouraging capability in promoting wound healing through antioxidant and anti-inflammatory activities, promotion of cell migration and antimicrobial effects. It is observed that the strong antioxidant properties of SeNPs help mitigate oxidative stress in wound tissues (Wang et al., 2021). This property is vital for protecting cells from damage during the inflammatory phase of healing. Selenium nanoparticles can modulate inflammatory responses, reducing excessive inflammation that can impair wound healing. The enhancement of multiplication and invasion of fibroblasts and keratinocytes that are crucial for new tissue formation and re-epithelialization by selenium nanoparticles is also studied (Hamed et al., 2023). Research studies showed the effectiveness of SeNPs on mouse fibroblast cell lines for excellent wound healing properties (Cittrarasu et al., 2021). It has been shown that SeNPs can be incorporated into hydrogels and other biomaterials for sustained release, providing a prolonged therapeutic effect in wound healing applications (Jiang et al., 2024). Table 5 shows the therapeutic roles of selenium in various health conditions.

4.2. Selenium nanoparticles and their applications in agriculture

SeNPs have garnered interest in agriculture due to their unique properties and potential benefits for plant growth and crop yield (Bano et al., 2021; Selim et al., 2022). At low concentrations, they can stimulate seed germination and promote

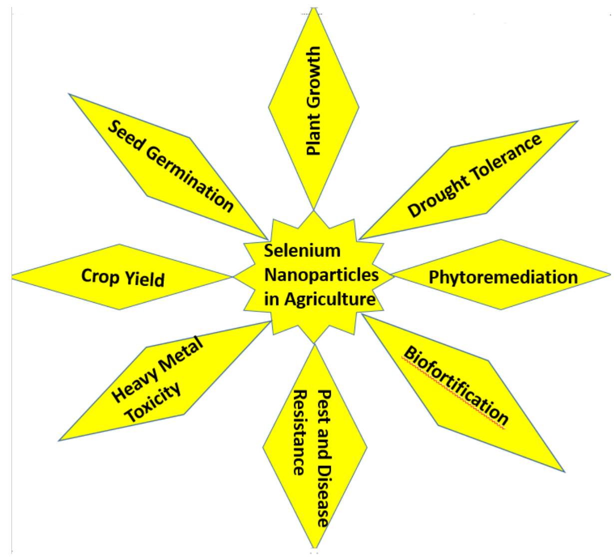

Figure 4. Applications of Selenium nanoparticles in agriculture

Table 5.

Therapeutic role of selenium in various health conditions:

Condition	Description	Reference
Hypothyroidism	Selenium is important for thyroid hormone synthesis; may improve thyroid function.	(Varghese et al., 2025)
Autoimmune Thyroiditis	Selenium may help reduce thyroid peroxidase antibodies.	(Huwiler et al., 2024)
Cancer	Potential protective effects against lung, colon and prostate cancer.	(Spyridopoulou et al., 2021)
Cognitive Decline and Neurodegenerative Diseases	Possible role in mitigating the chances of Alzheimer's disease.	(Zhou et al., 2023) (Chen et al., 2021)
HIV/AIDS	Selenium supplementation may boost defence mechanism and lessen viral load.	(Stone et al., 2010), (Muzembo et al., 2019) (Rojekar et al., 2022)
Asthma	Antioxidant properties may help decrease inflammation in asthma patients.	(Jiang et al., 2024)
Infertility	Important for sperm production; may improve male fertility.	(Refaat et al., 2024) (Yuan et al., 2024) (Paul et al., 2024)
Diabetes	May improve insulin sensitivity, though results are mixed.	(Zhao et al., 2022)
Chronic Fatigue Syndrome	Selenium may help alleviate symptoms related to oxidative stress.	(Castro-Marrero et al., 2022)
Selenium Deficiency Syndromes	Health issues related to low selenium levels, including impaired immune function.	(Rayman, 2020)
Stroke	Selenoproteins in brain comtributes to the free radical defence system in brain function.	(Amani et al., 2019)
Tuberculosis	Selenium enhances immunity, modulates macrophage function, induce autophagy.	(Ifijen et al., 2023)

Table 6.
Applications of Selenium nanoparticles in agriculture and their probable mechanism of action.

Activity	Application	Mechanism of Action	Reference
Plant Growth	Selenium nanoparticles can stimulate plant growth.	By nutrient absorption, photosynthesis, metabolism and antioxidant activity.	(Bano et al., 2021)
Drought Tolerance	SeNPs enhance the ability of plants to withstand drought stress.	By reducing oxidative damage and improving water retention.	(Zeeshan et al., 2024)
Seed Germination	SeNPs can promote seed germination.	By improving the metabolic processes and boosting the activity of enzymes.	(El-Badri et al., 2021)
Heavy Metal Toxicity	SeNPs can mitigate the toxic effects of heavy metals in plants.	By reducing oxidative stress and enhancing detoxification processes.	(Zhu et al., 2022)
Phytoremediation	Selenium nanoparticles can be utilized to enhance phytoremediation processes in soils contaminated with toxic metals.	By improving the overall soil quality by converting the non-compliant minerals to biocompatible mode.	(Sardar et al., 2022)
Antioxidant Defense System	SeNPs enhance the antioxidant property of the plants.	By production of antioxidant enzymes like catalase and superoxide dismutase, improving plant defense against environmental stresses.	(Morales-Espinoza et al., 2019)
Biofortification	Enhancement of Nutritional Value	SeNPs have been shown to increase the selenium content in edible crops, enhancing their nutritional value, particularly for human health.	(Song et al., 2023)
Pest and Disease Resistance	SeNPs have been shown to increase the resistance of plants to fungal, bacterial, and viral infections.	By inhibiting the growth of plant pathogens by disruption of cell membrane.	(Ikram et al., 2022)
Crop Yield	Improvement of crop yield	By enhancing their metabolic functions and stress tolerance, especially under suboptimal conditions.	(Selim et al., 2022)

root and shoot growth (El-Badri et al., 2021). SeNPs are used as fertilizers to regulate crop growth and produce food rich in selenium, which can prevent Keshan's disease (Song et al., 2023). Researchers studied the effect of biogenically synthesized SeNPs on Huanglongbing or Yellow Dragon Disease in Kinnow Mandarin plants. SeNPs of 75 mg/L were found to be most effective (Ikram et al., 2022). Researchers studied the effect of SeNPs on the tolerance level of the Pak choi plant to cadmium, lead, and mercury. The significant effect shown by SeNPs in mitigating the effect of the heavy metals on the plant was attributed to the increased activity of the root, inhibition of heavy metals migration in the plant, activation of the antioxidant system for scavenging of ROS, and minimized levels of malondialdehyde (Zhu et al., 2022). Table 6 shows the application of SeNPs and their possible mechanism of action in agriculture.

5. Conclusion

Green synthesis of mono- and bimetallic selenium nanoparticles represents a rapidly advancing frontier at the intersection of nanotechnology, biotechnology, and sustainable chemistry. By utilizing biological resources such as plant extracts and microorganisms, eco-friendly synthetic routes not only minimize environmental impact but also impart unique surface functionalities that enhance nanoparticle stability and bioactivity. These green-synthesized selenium-based nanoparticles exhibit remarkable antioxidant, antimicrobial, anticancer, anti-inflammatory, and drug-delivery potential, highlighting their relevance in modern biomedical applications. Their ability to improve plant growth, enhance nutrient uptake, suppress phytopathogens, and promote stress tolerance underscores their emerging role in sustainable agriculture. Bimetallic SeNPs, in particular, offer synergistic physicochemical and biological properties superior to their monometallic counterparts, though their mechanisms of action have not been explored completely. Despite notable progress, challenges persist related to scalability, batch-to-batch reproducibility, long-term toxicity, environmental fate, and regulatory frameworks. To fully translate these materials into clinical and agricultural practice, future studies must aim to standardize green synthesis protocols, establish comprehensive safety profiles, and explore targeted functionalization strategies for improved efficacy and specificity. Green-synthesized mono and bimetallic selenium nanoparticles hold significant promise as next-generation materials for sustainable biomedical therapeutics and eco-friendly agricultural technologies. With continued interdisciplinary research, these nanomaterials are poised to contribute meaningfully to global health, food security, and environmental sustainability.

Author Contributions

Syeda Haseen Buvabi: Conceptualization; Data collection; Original draft preparation; Writing; Reviewing the first draft; Methodology discussion. Pasupuleti Visweswara Rao: Conceptualization; Supervision. Nethravathi: Reviewing the first draft; Methodology discussion. Sayeeda Shabana: Reviewing the first draft; Methodology discussion.

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