Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Green Phytogenic fabrication of SeNPs: Characterization and Applications

Muhammad Arslan Abid
Department of Chemistry, Superior University Lahore, Pakistan.
arslanabid328@gmail.com,
su74-mschw-s24-011@superior.edu.pk

Dr. Muhammad Atif
Department of Chemistry, Superior University Lahore, Pakistan.
muhammad.atif.fsd@superior.edu.pk

Salman Ali
Department of Chemistry, Superior University Lahore, Pakistan.
zsalman838@gmail.com

Dr. Ali Imran Mallhi
Department of Chemistry, Superior University Lahore, Pakistan.
imranmallhi72@gmail.com

ABSTRACT

Selenium nanoparticles (SeNPs) have attracted significant interest due to their unique redox and biological activities in biomedical, agricultural, and environmental contexts. Green, plant-mediated methods for synthesizing SeNPs leverage plant extracts rich in phytochemicals to reduce selenium salts and cap the resulting nanoparticles, providing an eco-friendly and biocompatible alternative to conventional chemical routes. Such methods often yield SeNPs with enhanced antioxidant and antimicrobial properties. This review systematically examines recent progress in plant-based SeNP fabrication, including the underlying reduction mechanisms, synthesis parameters, and physicochemical characterization techniques. We also highlight key findings on SeNP bioactivities – for example, their potent ROS-scavenging antioxidant effects and cytotoxic action against cancer cells – and discuss applications in health, agriculture, and pollution remediation. Finally, challenges related to toxicity, scalability, and standardization are addressed to guide future research.

Keywords: Green Phytogenic, fabrication, SeNPs

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Introduction

Nanomaterials synthesized via biological ("green") routes are increasingly favored for their sustainability [1]. In nanoparticle (NP) production, green synthesis – using plant extracts or microbes is considered one of the most economical and eco-friendly approaches, as it avoids toxic reagents and byproducts [2]. Plants provide abundant phytochemicals (polyphenols, flavonoids, terpenoids, etc.) that can simultaneously reduce metal salts and stabilize the formed NPs [3]. Selenium (Se) is an essential trace element, but its inorganic forms (selenite/selenate) are toxic at high levels [4]. Converting Se into elemental SeNPs mitigates toxicity while retaining biological function [5], [6]. Plant-derived SeNPs typically exhibit lower toxicity than inorganic Se and carry a "bio-organic" corona from the extract, which can enhance biocompatibility [7]. As a result, plant-mediated SeNPs have been explored for diverse roles – from nutritional supplementation to antimicrobial coatings [8]. For instance, green SeNPs have been shown to promote plant growth and stress tolerance (by improving soil fertility and nutrient uptake) while maintaining environmental safety [9]. Here, we first outline synthesis routes for SeNPs and their characterization, then survey the main application areas (antioxidant, antimicrobial, anticancer, agricultural, and environmental) supported by recent studies.

Synthesis methods of Se-NPs

Selenium nanoparticles can be produced by various methods classified as top-down or bottom-up approaches [10], [11], [12]. In the top-down approach, bulk selenium (e.g., powders or rods) is physically broken down to the nanoscale by techniques such as milling, laser ablation, or thermal decomposition [12]. This can yield large-scale quantities but often produces size distributions with irregular shapes and surface defects [12]. Conversely, the bottom-up approach assembles SeNPs from molecular precursors: typically, selenium salts (e.g., sodium selenite) are chemically or biologically reduced to Se atoms that nucleate and grow into nanoparticles [13]. The bottom-up method generally offers finer control over particle size and chemistry, since factors like temperature, pH, and reducing agents can be tuned to modulate nucleation and growth rates [10], [11], [12]. For example, in wet-chemical bottom-up synthesis, SeO_2 or selenious acid is mixed with a reducing agent (like ascorbic acid) and a stabilizer (such as a surfactant) to yield SeNPs of defined size and shape [14], [15].

Top-down approach

The top-down route begins with bulk selenium and relies on mechanical or physical forces to fragment it into nanoparticles [16], [17]. Although this can be done at large scale, the resulting Se-NPs often have wide size distributions and surface imperfections due to the harsh processing conditions [18]. Consequently, top-down methods are less commonly used for SeNPs in biomedicine or agriculture, where size uniformity and purity are critical [19]. Figure 1 illustrates the difference between top-down and bottom-up strategies, showing how bulk selenium is broken down versus built up from ions.

Bottom-up approach

Bottom-up synthesis constructs SeNPs atom-by-atom. In typical protocols, selenium salts (e.g., Na_2SeO_3 or Na_2SeO_4) are reduced (chemically or biologically) in solution, resulting in atomic Se that nucleates and grows into nanoparticles [20]. Self-assembly processes allow control of particle dimensions and surface coatings during growth [21].

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

For instance, adding a capping molecule during synthesis can limit growth and stabilize a narrow size range [21], [22], [23]. Compared to top-down, the bottom-up approach generally yields more uniform SeNPs, making it preferable for applications requiring consistent nanoparticle behavior [21].

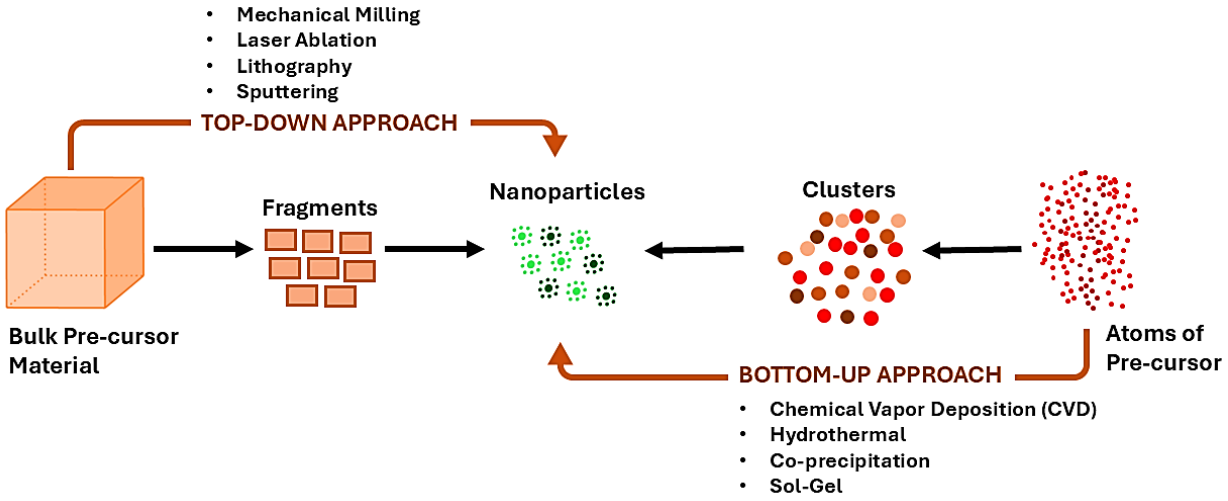

***Figure 1**: Schematic illustration of top-down & bottom-up nanoparticle fabrication approaches.*

Biogenic synthesis of Se-NPs

Biogenic (biological) synthesis exploits living organisms or extracts to produce SeNPs [12], [21], [21], [22], [23], [24]. By using plant-derived or microbial agents, biogenic methods achieve high yields in a single step under mild conditions [25]. Biological agents contain natural reducing compounds (e.g., enzymes, proteins, polyphenols) that convert soluble selenite/selenate into insoluble Se^0 and cap the formed NPs [26]. Biogenic synthesis is highly valued for its low cost, safety, and environmental compatibility [25].

Plant-mediated Se-NPs synthesis

Plant extracts are a particularly attractive biogenic system [27], [28], [29]. A variety of plant parts (leaves, fruits, roots, etc.) can be processed into aqueous extracts containing antioxidants and other phytochemicals [27], [28], [29]. When mixed with a selenium salt solution under controlled pH and temperature, the extract reduces Se^{4+} ions to nanoscale Se^0 and simultaneously stabilizes the particles. This "green synthesis" is simple and scalable: for example, boiling tea leaves or fruit peels in water can generate an extract that yields SeNPs in a matter of hours [30]. The active biomolecules (flavonoids, carotenoids, tannins, etc.) donate electrons to reduce Se and then bind to the nanoparticle surface, preventing aggregation [31]. Key factors influencing plant-mediated synthesis include extract concentration, reaction time, temperature, and selenium precursor concentration [32]. Importantly, plant-synthesized SeNPs often show excellent biocompatibility and exhibit functional groups (e.g., C–O, C–N, NH, COO–) from the capping agents on their surface [30], [32]. A suggested schematic of this process is shown in Figure 2.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Figure 2: *Plant mediated SeNPs synthesis using extract acting as reducing/capping agent.*

Bacteria-mediated Se-NP synthesis

Several bacterial species can also produce SeNPs by reducing selenium salts. In such methods, live bacterial cells or cell-free bacterial extracts are incubated with selenate/selenite under appropriate conditions [33], [34], [35], [36]. The bacterial enzymes and metabolites drive the reduction, yielding SeNPs either inside or outside the cells [33], [34], [35], [36]. Common examples include *Bacillus subtilis*, *Escherichia coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*, which have all been shown to produce stable SeNPs. Bacterial synthesis is attractive because of its high yield and ease of scale-up [33], [34], [35], [36]. Moreover, the process is eco-friendly and can generate uniformly small SeNPs capped with biological molecules [33], [34], [35], [36]. However, controlling batch variability and purifying the nanoparticles from bacterial components can be challenging in practice [33], [34], [35], [36].

Fungi-mediated Se-NP synthesis

Fungi (yeasts and molds) offer another green route to SeNPs. Filamentous fungi or yeast cells are incubated with selenium salts; their enzymes, proteins, and polysaccharides reduce Se to the nanoparticle form [37], [38]. Fungi-mediated synthesis often yields SeNPs with high stability and low toxicity. As with bacteria, factors such as fungal strain, precursor concentration, and incubation time affect nanoparticle size [37], [38]. Fungi like *Candida*, *Aspergillus*, and *Penicillium* species have been used to generate SeNPs that exhibit antimicrobial and anticancer activities. Overall, biological routes provide a sustainable means to produce SeNPs, with plant-based synthesis being the simplest and most widely applicable for large-scale use [37], [38].

Characterization of Se-NPs

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Physicochemical characterization is essential to confirm SeNP formation, size, morphology, and composition [39]. Key analytical techniques include:

- **Ultraviolet–visible (UV-Vis) spectroscopy.** SeNPs exhibit characteristic absorption in the UV region due to their size-dependent electronic transitions. UV-Vis spectra provide evidence of nanoparticle formation and approximate particle size [7], [23], [40], [41]. For example, SeNPs often show a distinctive plasmon peak between 200–400 nm. Monitoring the UV-Vis absorbance over time can also track reaction progress [7], [23], [40], [41]. Overall, UV-Vis spectroscopy offers a rapid way to verify SeNP synthesis and infer average particle dimensions [7], [23], [40], [41].

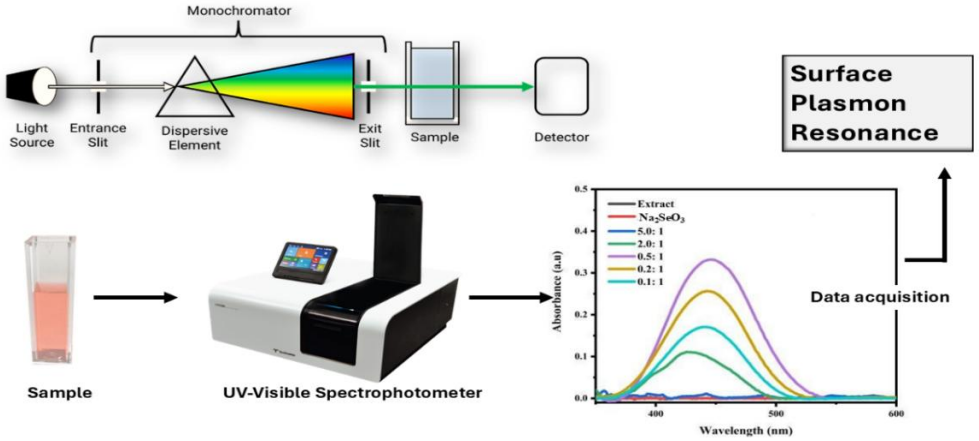

Figure 3: *UV-Visible Spectroscopy for characterization of SeNPs*

- **Fourier transform infrared (FTIR) spectroscopy.** FTIR identifies surface functional groups on SeNPs, confirming the presence of capping phytochemicals [42], [43]. In plant-mediated SeNPs, FTIR usually detects O–H, C=O, and C–O vibrations from polyphenols or proteins adsorbed on the nanoparticle surface [42], [43]. Characteristic peaks (e.g., around 1,375 cm^{-1}, 1,030 cm^{-1}, 1,462 cm^{-1}) have been associated with phenolic and aromatic bonds in the capping layer. FTIR thus helps verify that biological molecules from the extract remain attached to the SeNPs, which influence stability and activity [42], [43].

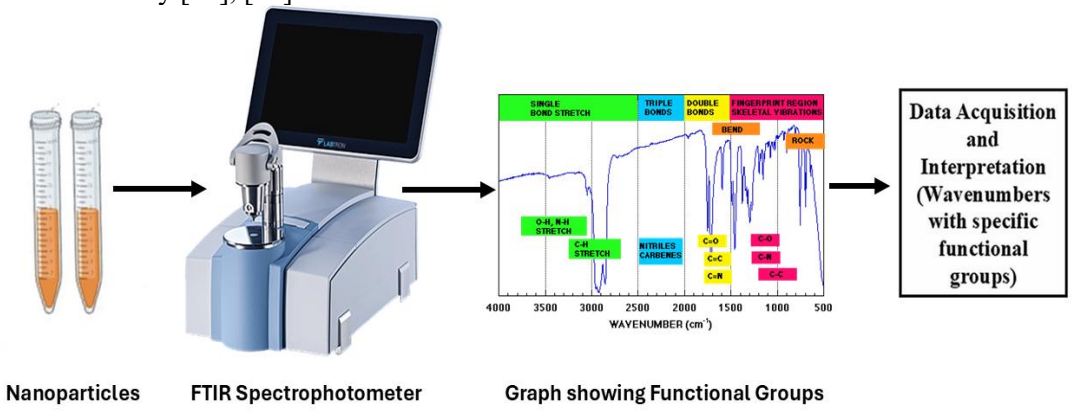

Figure 4: *FT-IR Spectroscopy for characterization of SeNPs*

- **Transmission electron microscopy (TEM).** TEM provides direct imaging of SeNP size, shape, and dispersion. High-resolution TEM micrographs allow precise measurement of nanoparticle diameter (down to a few nm) and reveal morphological

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

details [44], [45], [46]. For instance, SeNPs synthesized from plants are often spherical (40–90 nm) and uniformly distributed. TEM can also show any lattice fringes, indicating crystalline vs. amorphous structure [44], [45], [46]. Additionally, coupling TEM with energy-dispersive X-ray (EDX) detectors confirms elemental composition (see below) [44], [45], [46]. In summary, TEM is the gold standard for assessing SeNP morphology and verifying that biosynthesis produces the intended nanoscale particles [44], [45], [46].

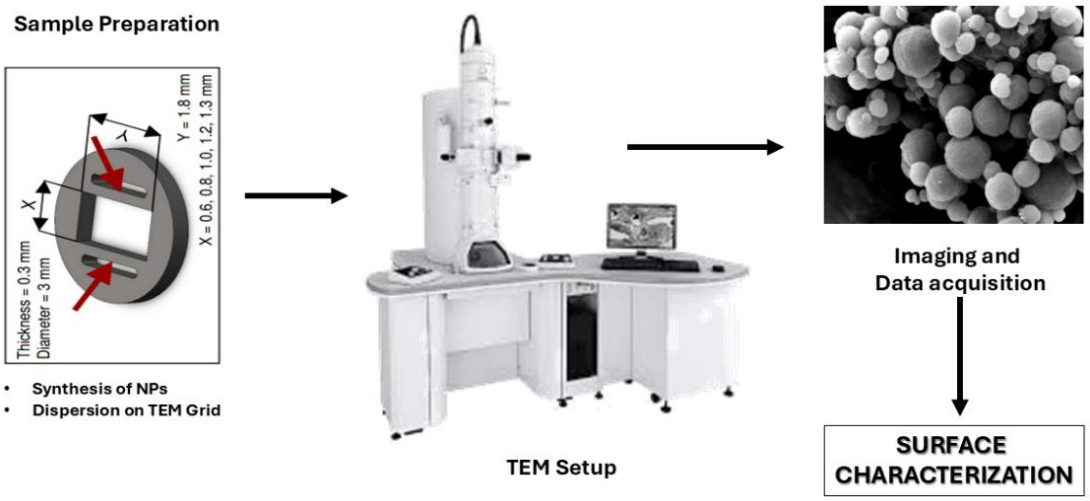

Figure 5: *Illustrative TEM Characterization of SeNPs*

- **Dynamic light scattering (DLS).** DLS measures SeNP size distribution and average hydrodynamic diameter in colloidal suspension. By analyzing fluctuations in scattered light due to Brownian motion, DLS yields the mean particle size and polydispersity index [47], [43]. It can also measure zeta potential, indicating nanoparticle surface charge and colloidal stability [47], [43]. In practice, DLS often reports larger diameters than TEM (since it includes the hydration layer and capping) [47], [43]. Nevertheless, DLS is a convenient method to quantify size distributions of SeNP samples and to optimize synthesis conditions for uniformity [47], [43].

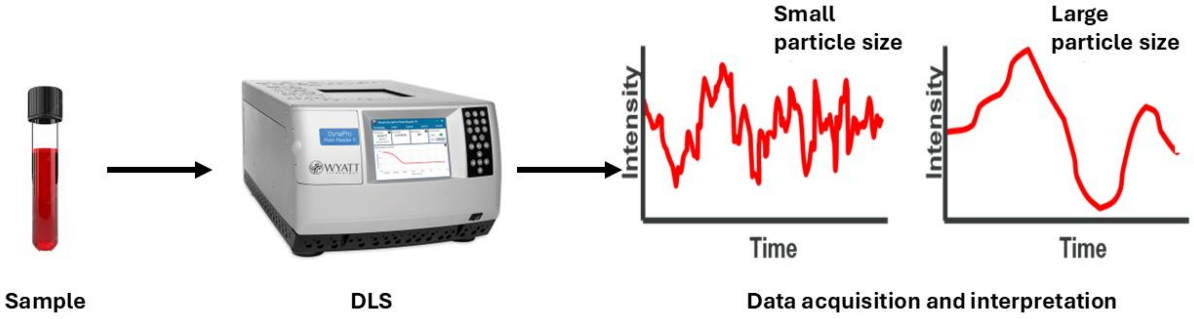

Figure 6: *DLS characterization of SeNPs*

- **Energy dispersive X-ray spectroscopy (EDX).** Attached to an electron microscope, EDX analyzes the elemental composition of SeNPs [48], [49]. When SeNPs are irradiated, characteristic X-ray emissions reveal which elements are present. EDX spectra of green-synthesized SeNPs typically show strong selenium peaks at 11.2 keV and 12.4 keV, confirming the presence of Se^0. The relative intensities of these peaks can quantify the selenium content and detect impurities (e.g., from precursors or

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

capping agents) [48], [49]. EDX thus ensures the synthesized NPs are indeed Se and helps verify purity [48], [49].

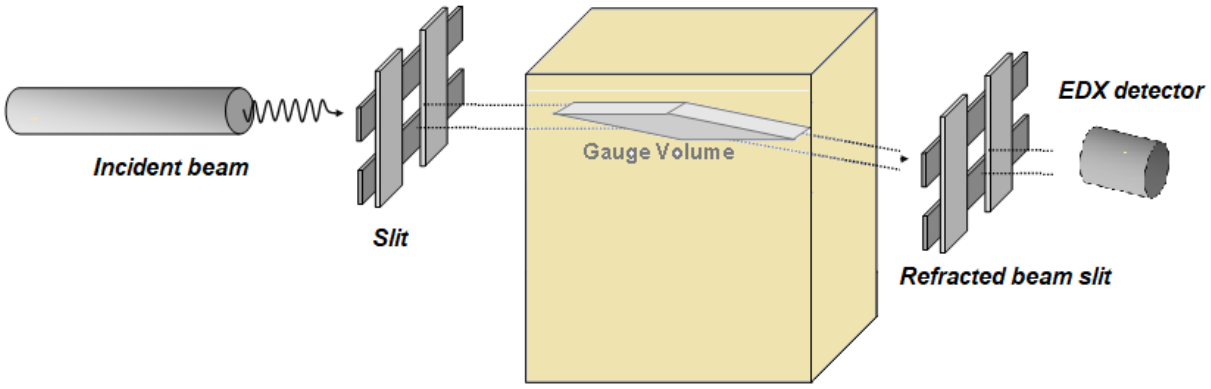

Figure 7: *Schematic illustration of Energy dispersive X-Ray Spectroscopy of SeNPs*

Collectively, these characterization techniques (often presented in Figures 3–7) provide a complete profile of SeNPs – confirming their nanoscale size, chemical identity, and the presence of bio-organic surface groups from the plant extract.

Table 1: *Characterization techniques used for selenium nanoparticles (SeNPs) and typical findings reported for plant-mediated synthesis.*

Technique	Parameter Measured	Typical Findings for SeNPs	References
UV-Vis	Absorption peak	Broad SPR peak in ~200–500 nm range (commonly ~270–300 nm)	[7], [23], [40], [41]
TEM/SEM	Size and morphology	Generally spherical particles; diameter typically <100 nm (often ~20–90 nm)	[44], [45], [46]
XRD	Crystal structure	Distinct Bragg peaks (2θ ~10–80°) confirming nanocrystalline Se (hexagonal phase)	[48], [49]
FTIR	Surface functional groups	Vibrational bands for capping ligands: –OH, –NH_2, –C=O, –CO, –COOH groups	[42], [43]
DLS	Hydrodynamic diameter	Hydrodynamic size usually larger than core (example: ~140 nm) ; PDI often <0.3	[47], [43]
Zeta potential	Surface charge (mV)	Typically moderately negative (≈–20 to –30 mV) indicating colloidal stability	[47], [43]

Applications of Se-NPs

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Plant-mediated SeNPs exhibit a broad spectrum of beneficial activities, leveraging selenium's bioactivity and the unique properties of the nanoscale. Major application areas include biomedicine (antioxidant, antimicrobial, anticancer), agriculture (nanofertilizers, stress protection), and environmental remediation [50], [51], [52]. The reported mechanisms often involve modulation of redox processes and disruption of pathological targets, as outlined below.

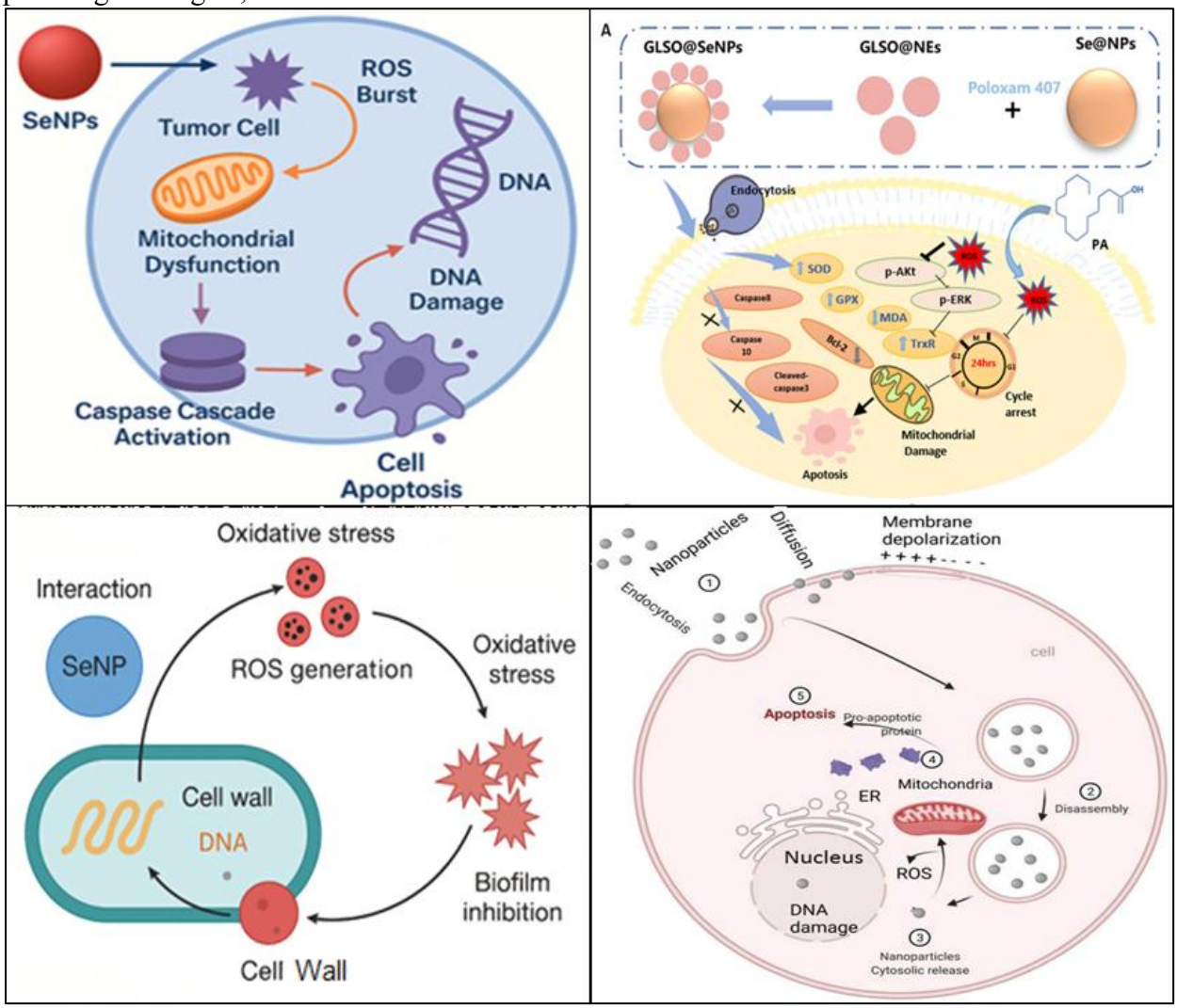

Figure 8: *Schematic representation of the bioactivities of plant-mediated (SeNPs).*

Se-NPs in anticancer applications

SeNPs are being extensively studied as anticancer agents due to their ability to selectively induce oxidative stress in tumor cells [53]. Cancer cells typically have higher baseline reactive oxygen species (ROS) and weaker antioxidant defenses than normal cells, so a further increase in ROS can trigger apoptosis or necroptosis in tumors while sparing healthy tissue [54]. For example, plant-derived SeNPs have been shown to raise ROS levels and activate cell death pathways in prostate, breast, and liver cancer cell lines [54]. In one study, SeNPs induced necroptotic death in PC-3 prostate cancer cells at low doses (~2 µg/mL), accompanied by upregulation of TNF and RIP1 genes

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 3 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

[55]. Similarly, SeNP treatment of MCF-7 breast cancer cells caused classic apoptotic features (DNA fragmentation, caspase activation) and cell-cycle arrest [56]. Reported IC_{50} values for SeNPs against various cancer cells range from ~2 µg/mL to 100 µg/mL, while concentrations well above those (e.g. >300 µg/mL) may be required to affect normal cells. This indicates a favorable selectivity index, partly attributed to the bio-organic capping enhancing uptake by cancer cells and the differential redox response [57], [58]. Moreover, SeNPs can synergize with chemotherapeutic drugs: conjugating SeNPs with doxorubicin, for instance, enhanced breast cancer cell kill relative to the drug alone, by combining SeNP-induced ROS with improved drug delivery [57], [58]. A summary of reported anticancer efficacy (IC_{50} values) alongside antimicrobial data is provided in Table 1.

Se-NPs in antimicrobial applications

Green SeNPs have demonstrated broad-spectrum antimicrobial effects against bacteria, fungi, and viruses [59]. These nanoparticles interact with microbial cells via multiple mechanisms. They can bind to and disrupt cell walls/membranes, causing structural damage and loss of integrity [59]. Concurrently, the selenium surface redox activity generates ROS (superoxide, hydroxyl radicals) in the vicinity of microbes, overwhelming their antioxidant defenses. This oxidative assault damages proteins, lipids, and DNA in pathogens [42], [47], [60], [61]. Additionally, SeNPs may bind to thiol-containing enzymes in microbes, impairing metabolism. Importantly, many plant-synthesized SeNPs achieve bacterial or fungal inhibition at concentrations nontoxic to mammalian cells, suggesting a useful therapeutic window. For example, SeNPs capped with plant flavonoids have killed drug-resistant *E. coli* and *S. aureus* strains at low tens of µg/mL, outperforming some antibiotics. SeNPs have also shown antifungal activity: in vitro tests reported nearly 100% inhibition of *Aspergillus* and *Penicillium* growth at moderate SeNP doses [42], [47], [60], [61]. The mode of fungal inhibition is analogous, involving membrane perturbation and ROS. Because selenium is essential at trace levels but toxic in excess, microbial cells lack an easy resistance mechanism against SeNPs – a potential advantage over conventional antibiotics [62]. These findings suggest SeNPs could be developed as novel antimicrobials for healthcare or food safety. (Table 1 lists selected MIC/IC_{50} data for SeNPs against pathogens and cancer cells, illustrating their potency.)

Se-NPs in antifungal applications

In addition to antibacterial activity, SeNPs have been shown to inhibit fungal pathogens. Studies report that plant-derived SeNPs can block growth of *Aspergillus*, *Penicillium*, *Candida*, and other fungi [63]. The antifungal mechanism parallels the antibacterial one: SeNPs associate with fungal cell surfaces, induce oxidative stress, and interfere with enzyme systems necessary for spore germination and hyphal growth [64]. For instance, Ficus platyphylla-extract SeNPs achieved 97–100% growth inhibition of *Aspergillus* and *Penicillium* species in vitro. Such broad antifungal efficacy makes SeNPs promising for agricultural or medical antifungal applications [64]. We note that these results are an emerging area; more in vivo and formulation studies will be needed to translate SeNP antifungal use into practical products.

Table 2: *Anticancer and antimicrobial activities of plant-mediated selenium nanoparticles (SeNPs), their biological mechanisms, and effective concentrations.*

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

SeNP source (plant extract)	Target cell/pathogen	Mechanism	IC_{50} / MIC (µg/mL)	Reference
Cassia javanica (flower extract)	*Staphylococcus aureus* (Gram+)	ROS generation; cell membrane disruption	MIC = 500 µg/mL	[42], [47], [60], [61]
Cassia javanica (flower extract)	*Escherichia coli* (Gram–)	ROS generation; cell membrane disruption	MIC = 250 µg/mL	[60], [61], [65], [66]
Cassia javanica (flower extract)	*Candida albicans* (fungus)	ROS generation; membrane integrity loss	MIC = 62.5 µg/mL	[60], [61], [65], [66]
Moringa oleifera (leaf extract)	*Staphylococcus aureus*, *E. coli*	Cell wall disruption; oxidative stress	MIC ≈ 58.2 µg/mL (both)	[22]
Vaccinium arctostaphylos (fruit extract)	4T1 breast cancer cells	Induces apoptosis (via ROS)	IC_{50} ≈ 84.2 µg/mL	[57], [58]
Azadirachta indica (leaf extract)	HCT116 (colon cancer)	Induces apoptosis (via ROS)	IC_{50} ≈ 127.2 µg/mL	[67], [58]
Azadirachta indica (leaf extract)	MDA-MB-231 (breast cancer)	Induces apoptosis (via ROS)	IC_{50} ≈ 263.4 µg/mL	[67], [58]
Azadirachta indica (leaf extract)	HUH7 (liver cancer)	Induces apoptosis (via ROS)	IC_{50} ≈ 330.5 µg/mL	[67], [58]

Se-NPs in antidiabetic applications

Some research has investigated SeNPs for managing diabetes by modulating oxidative stress and insulin signaling. Unlike chemical antidiabetic drugs, SeNPs can mimic nutritional selenium's effect on redox balance [68]. For example, an animal study found that administering green-synthesized SeNPs to diabetic mice improved glycemic control: the nanoparticles increased levels of endogenous antioxidant enzymes (glutathione peroxidase, superoxide dismutase) and reduced fasting blood glucose and lipid peroxidation [69]. In that study, SeNP-treated diabetic rats showed significantly lower serum glucose and malondialdehyde levels compared to untreated diabetics, indicating protection against oxidative damage [69]. These findings suggest SeNPs (or SeNP supplements) might help alleviate diabetes-related oxidative stress. However, research in this area is still preliminary. The exact mechanisms by which SeNPs influence pancreatic cells and insulin pathways remain to be clarified. Nonetheless, the low toxicity of SeNPs makes them interesting candidates for further investigation as nutraceutical or adjunct therapies in metabolic disorders.

Se-NPs in Agriculture and Environment

Beyond biomedical and antimicrobial applications, selenium nanoparticles synthesized through plant-mediated routes have also demonstrated promising potential in agriculture and environmental remediation [41], [65]. For instance, SeNPs derived from *Cocculus pendulus* leaf extract were reported to significantly enhance plant growth, increasing the number of

Online ISSN 3007-3197
Print ISSN 3007-3189

flowers and overall biomass under conditions of heavy-metal stress [70]. Importantly, these SeNPs simultaneously promoted phytoremediation by improving the uptake and detoxification of heavy metals from contaminated soils, suggesting a dual role in supporting plant vigor and soil cleanup. Similarly, priming *Spinacia oleracea* (spinach) seeds with green-synthesized SeNPs alleviated arsenic-induced toxicity by improving photosynthetic efficiency, strengthening antioxidant defense mechanisms, and ultimately enhancing plant resilience [17], [71]. This treatment also reduced arsenic accumulation in plant tissues, with root concentrations nearly halved compared to untreated controls, underscoring the potential of SeNPs in mitigating heavy-metal uptake [71].

Table 3: ***Agricultural and Environmental Applications of Plant-Derived SeNPs***

Plant Source	Agricultural Benefit	Environmental Benefit	Reference
Cocculus pendulus (leaf extract)	Enhanced plant growth (↑ flowers, fresh/dry biomass) under heavy-metal stress	Promoted phytoremediation of heavy metals (improved soil cleanup)	[70]
Spinacia oleracea (Spinach, seed-priming with SeNPs)	Alleviated arsenic stress (improved photosynthesis and antioxidant defense)	Reduced As accumulation in plant tissues (2× lower in roots)	[71]

Collectively, these findings highlight the role of plant-mediated SeNPs not only as bio-nanofertilizers that stimulate plant growth and stress tolerance but also as effective agents for environmental decontamination, particularly in the remediation of toxic elements such as arsenic and heavy metals.

Toxicity assessment

The biosafety of SeNPs is a crucial consideration. In vitro and in vivo studies suggest that plant-mediated SeNPs tend to be significantly less toxic than equivalent doses of inorganic selenium salts (selenite, selenate). The “nano” form releases selenium more slowly, and the biological capping can reduce nonspecific uptake [72].

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

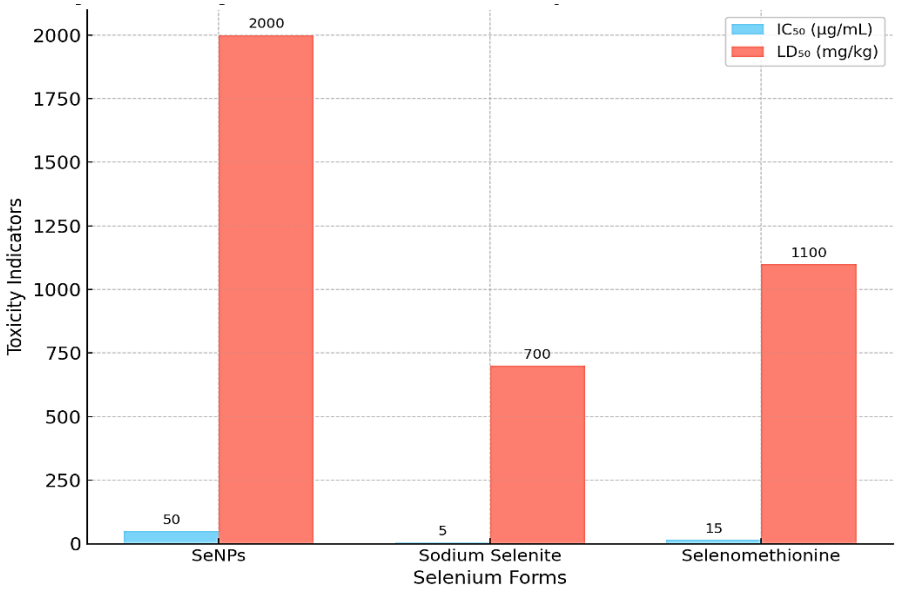

Figure 9: *Comparative toxicity and safety profiles of selenium forms.*

Plant-mediated selenium nanoparticles (SeNPs) demonstrate significantly higher IC_{50} values (indicating lower cytotoxicity to normal cells) and higher LD_{50} values (indicating lower systemic toxicity) compared with sodium selenite and Selenomethionine. These data highlight the improved safety margin of SeNPs at therapeutic doses [73]. For example, a toxicity study found that mice exposed to SeNPs showed fewer adverse effects on the liver and blood than those given sodium selenite or selenomethionine at the same dose [74], [75]. In cell culture, normal mammalian cells often tolerate higher concentrations of SeNPs than microbial or cancerous cells do. Key toxicity determinants include particle size, dose, and surface coating. Smaller SeNPs or high doses can induce toxicity, particularly via oxidative stress if antioxidant defenses are overwhelmed. Current evidence recommends keeping therapeutic SeNP doses below levels that raise cellular ROS excessively [75], [76].

Nonetheless, comprehensive safety evaluation is still needed. Most studies to date are short-term or in vitro. Long-term biodistribution, bioaccumulation, and environmental impact of SeNPs require careful assessment. Regulators will demand rigorous nanotoxicology data before SeNPs can be approved for clinical or agricultural use. In particular, it is essential to verify that the green synthesis process does not introduce contaminants and that SeNP preparations are well-purified (for example, by thorough washing and centrifugation) before use. Addressing these issues – through standardized production protocols and systematic toxicology studies – will be key to translating SeNP research into safe, real-world applications [77].

Conclusion

Plant-mediated synthesis of selenium nanoparticles represents a convergence of green chemistry and nanotechnology with wide-reaching applications. By using botanical extracts as reactors, researchers can produce SeNPs in an economical and eco-friendly manner, yielding biocompatible particles with antioxidant and antimicrobial coatings. The resulting SeNPs have demonstrated versatility: they act as potent free-radical

Online ISSN 3007-3197
Print ISSN 3007-3189

scavengers, broad-spectrum antimicrobials, and cancer-cell suppressors in laboratory studies. They have also shown promise in enhancing plant growth and stress tolerance (serving as nano-fertilizers) and in remediating environmental pollutants (by adsorbing heavy metals or catalyzing degradation of organics). The aggregated evidence (summarized in Tables 1–3 and Figures 1–2) indicates that plant-derived SeNPs can bridge disparate fields – from medicine and agriculture to water treatment – under the umbrella of sustainable nanotechnology.

However, realizing the full potential of SeNPs will require overcoming several challenges. Reproducibility and scale-up of green synthesis must be addressed: batch-to-batch consistency is hindered by natural variability in plant extracts, so standardizing extract preparation and exploring continuous-flow or reactor-based synthesis strategies will be important. Mechanistic understanding of SeNP formation and action also lags; future work should identify the specific phytochemicals driving Se^{4+} reduction and detail the molecular pathways by which SeNPs affect cells. Safety and regulatory considerations will play a central role: while preliminary findings suggest SeNPs have lower toxicity than inorganic forms, comprehensive in vivo testing and environmental impact studies are needed. Finally, interdisciplinary innovation – for example, combining SeNPs with smart delivery systems or other nanomaterials may yield novel hybrid technologies that overcome current limitations.

In summary, plant-based SeNPs exemplify how low-cost, green nanofabrication can produce multifunctional materials. If challenges in standardization, characterization, and safety are met, these nanoparticles are poised to become valuable tools in healthcare, sustainable agriculture, and environmental protection. Continued collaboration among chemists, biologists, agronomists, and engineers will be essential to translate laboratory insights into practical, Scopus-indexed applications for this exciting nanomaterial.

References

[1] N. Joudeh and D. Linke, “Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists,” *J. Nanobiotechnology*, vol. 20, no. 1, p. 262, June 2022, doi: 10.1186/s12951-022-01477-8.

[2] F. Zanbili and A. Poursattar Marjani, “Innovative green and bio-based approaches for photosensitive nanoparticle synthesis: a review on methodologies, characterization, and applications,” *Micro Nano Syst. Lett.*, vol. 13, no. 1, p. 3, Mar. 2025, doi: 10.1186/s40486-025-00223-7.

[3] R. Nain, H. Patel, M. Chahar, S. Kumar, D. Rohilla, and M. Pal, “Biosynthesized metallic nanoparticles for sustainable environmental remediation: mechanisms, applications, and future perspectives,” *Discov. Chem.*, vol. 2, no. 1, p. 124, May 2025, doi: 10.1007/s44371-025-00203-1.

[4] M. Kieliszek, I. Bano, and H. Zare, “A Comprehensive Review on Selenium and Its Effects on Human Health and Distribution in Middle Eastern Countries,” *Biol. Trace Elem. Res.*, vol. 200, no. 3, pp. 971–987, Mar. 2022, doi: 10.1007/s12011-021-02716-z.

Online ISSN 3007-3197
Print ISSN 3007-3189

[5] I. Bano, S. Skalickova, S. Arbab, L. Urbankova, and P. Horky, "Toxicological effects of nanoselenium in animals," *J. Anim. Sci. Biotechnol.*, vol. 13, no. 1, p. 72, Dec. 2022, doi: 10.1186/s40104-022-00722-2.

[6] Z. Khan, T. C. Thounaojam, D. Chowdhury, and H. Upadhyaya, "The role of selenium and nano selenium on physiological responses in plant: a review," *Plant Growth Regul.*, vol. 100, no. 2, pp. 409–433, June 2023, doi: 10.1007/s10725-023-00988-0.

[7] K. Pyrzynska, "Plant Extracts for Production of Functionalized Selenium Nanoparticles," *Materials*, vol. 17, no. 15, p. 3748, July 2024, doi: 10.3390/ma17153748.

[8] C. Su, K. Huang, H.-H. Li, Y.-G. Lu, and D.-L. Zheng, "Antibacterial Properties of Functionalized Gold Nanoparticles and Their Application in Oral Biology," *J. Nanomater.*, vol. 2020, pp. 1–13, Nov. 2020, doi: 10.1155/2020/5616379.

[9] S. H. Nile *et al.*, "Nano-priming as emerging seed priming technology for sustainable agriculture—recent developments and future perspectives," *J. Nanobiotechnology*, vol. 20, no. 1, p. 254, Dec. 2022, doi: 10.1186/s12951-022-01423-8.

[10] N. Joudeh and D. Linke, "Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists," *J. Nanobiotechnology*, vol. 20, no. 1, p. 262, June 2022, doi: 10.1186/s12951-022-01477-8.

[11] A. Aziz, H. Shaikh, A. Abbas, K. E. Zehra, and B. Javed, "Microscopic Techniques for Nanomaterials Characterization: A Concise Review," *Microsc. Res. Tech.*, vol. 88, no. 5, pp. 1599–1614, May 2025, doi: 10.1002/jemt.24799.

[12] I. Ijaz, E. Gilani, A. Nazir, and A. Bukhari, "Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles," *Green Chem. Lett. Rev.*, vol. 13, no. 3, pp. 223–245, July 2020, doi: 10.1080/17518253.2020.1802517.

[13] A. M. El-Badri *et al.*, "Comparative efficacy of bio-selenium nanoparticles and sodium selenite on morpho-physiochemical attributes under normal and salt stress conditions, besides selenium detoxification pathways in Brassica napus L.," *J. Nanobiotechnology*, vol. 20, no. 1, p. 163, Dec. 2022, doi: 10.1186/s12951-022-01370-4.

[14] N. Maldonado-Luna, S. Bailón-Ruiz, M. Reyes-Blas, and O. J. Perales-Perez, "Synthesis and characterization of Se-based nanoparticles as potential generators of reactive oxygen species," *MRS Adv.*, vol. 4, no. 7, pp. 419–424, Feb. 2019, doi: 10.1557/adv.2019.137.

[15] A. E. Abdelhamid, E. H. Ahmed, H. M. Awad, and M. M. H. Ayoub, "Synthesis and cytotoxic activities of selenium nanoparticles incorporated nano-chitosan," *Polym. Bull.*, vol. 81, no. 2, pp. 1421–1437, Jan. 2024, doi: 10.1007/s00289-023-04768-8.

[16] R. Abbasi, G. Shineh, M. Mobaraki, S. Doughty, and L. Tayebi, "Structural parameters of nanoparticles affecting their toxicity for biomedical applications: a review," *J. Nanoparticle Res.*, vol. 25, no. 3, p. 43, Mar. 2023, doi: 10.1007/s11051-023-05690-w.

Online ISSN 3007-3197
Print ISSN 3007-3189

[17] S. H. Nile *et al.*, "Nano-priming as emerging seed priming technology for sustainable agriculture—recent developments and future perspectives," *J. Nanobiotechnology*, vol. 20, no. 1, p. 254, Dec. 2022, doi: 10.1186/s12951-022-01423-8.

[18] R. Abbasi, G. Shineh, M. Mobaraki, S. Doughty, and L. Tayebi, "Structural parameters of nanoparticles affecting their toxicity for biomedical applications: a review," *J. Nanoparticle Res.*, vol. 25, no. 3, p. 43, Mar. 2023, doi: 10.1007/s11051-023-05690-w.

[19] S. S. S. Ibrahim, Y. N. Ansari, A. V. Puri, V. V. Patil, S. S. Gaikwad, and R. A. Haroon, "Recent Progress in the Green Synthesis, Characterization, and Applications of Selenium Nanoparticles," *BIO Integr.*, vol. 5, no. 1, 2024, doi: 10.15212/bioi-2024-0063.

[20] Ch. Ramamurthy *et al.*, "Green synthesis and characterization of selenium nanoparticles and its augmented cytotoxicity with doxorubicin on cancer cells," *Bioprocess Biosyst. Eng.*, vol. 36, no. 8, pp. 1131–1139, Aug. 2013, doi: 10.1007/s00449-012-0867-1.

[21] S. S. S. Ibrahim, Y. N. Ansari, A. V. Puri, V. V. Patil, S. S. Gaikwad, and R. A. Haroon, "Recent Progress in the Green Synthesis, Characterization, and Applications of Selenium Nanoparticles," *BIO Integr.*, vol. 5, no. 1, 2024, doi: 10.15212/bioi-2024-0063.

[22] A. A. Al-saeed, M. H. Risan, and T. S. Al-rubaye, "Green-Synthesised Selenium Nanoparticles Using Moringa Oleifera Leaf Extract: Characterization And Antibacterial Activity," *Int. J. Environ. Sci.*, vol. 11, no. 21, 2025.

[23] N. Srivastava and M. Mukhopadhyay, "Green synthesis and structural characterization of selenium nanoparticles and assessment of their antimicrobial property," *Bioprocess Biosyst. Eng.*, vol. 38, no. 9, pp. 1723–1730, Sept. 2015, doi: 10.1007/s00449-015-1413-8.

[24] F. Zanbili and A. Poursattar Marjani, "Innovative green and bio-based approaches for photosensitive nanoparticle synthesis: a review on methodologies, characterization, and applications," *Micro Nano Syst. Lett.*, vol. 13, no. 1, p. 3, Mar. 2025, doi: 10.1186/s40486-025-00223-7.

[25] J. K. Patra *et al.*, "Nano based drug delivery systems: recent developments and future prospects," *J. Nanobiotechnology*, vol. 16, no. 1, p. 71, Dec. 2018, doi: 10.1186/s12951-018-0392-8.

[26] K. S. Prasad and K. Selvaraj, "Biogenic Synthesis of Selenium Nanoparticles and Their Effect on As(III)-Induced Toxicity on Human Lymphocytes," *Biol. Trace Elem. Res.*, vol. 157, no. 3, pp. 275–283, Mar. 2014, doi: 10.1007/s12011-014-9891-0.

[27] A. A. Zaky, M. U. Akram, K. Rybak, D. Witrowa-Rajchert, and M. Nowacka, "Bioactive compounds from plants and by-products: Novel extraction methods, applications, and limitations," *AIMS Mol. Sci.*, vol. 11, no. 2, pp. 150–188, 2024, doi: 10.3934/molsci.2024010.

[28] I. Usman *et al.*, "Traditional and innovative approaches for the extraction of bioactive compounds," *Int. J. Food Prop.*, vol. 25, no. 1, pp. 1215–1233, Dec. 2022, doi: 10.1080/10942912.2022.2074030.

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

[29] A. I. Osman *et al.*, "Synthesis of green nanoparticles for energy, biomedical, environmental, agricultural, and food applications: A review," *Environ. Chem. Lett.*, vol. 22, no. 2, pp. 841–887, Apr. 2024, doi: 10.1007/s10311-023-01682-3.

[30] K. S. Prasad and K. Selvaraj, "Biogenic Synthesis of Selenium Nanoparticles and Their Effect on As(III)-Induced Toxicity on Human Lymphocytes," *Biol. Trace Elem. Res.*, vol. 157, no. 3, pp. 275–283, Mar. 2014, doi: 10.1007/s12011-014-9891-0.

[31] V. Alagesan and S. Venugopal, "Green Synthesis of Selenium Nanoparticle Using Leaves Extract of Withania somnifera and Its Biological Applications and Photocatalytic Activities," *BioNanoScience*, vol. 9, no. 1, pp. 105–116, Mar. 2019, doi: 10.1007/s12668-018-0566-8.

[32] J. J. O. Garza-García *et al.*, "Selenium nanoparticles based on Amphipterygium glaucum extract with antibacterial, antioxidant, and plant biostimulant properties," *J. Nanobiotechnology*, vol. 21, no. 1, p. 252, Aug. 2023, doi: 10.1186/s12951-023-02027-6.

[33] S. Dhanjal and S. Cameotra, "Aerobic biogenesis of selenium nanospheres by Bacillus cereus isolated from coalmine soil," *Microb. Cell Factories*, vol. 9, no. 1, p. 52, 2010, doi: 10.1186/1475-2859-9-52.

[34] A. J. Kora, "Bacillus cereus, selenite-reducing bacterium from contaminated lake of an industrial area: a renewable nanofactory for the synthesis of selenium nanoparticles," *Bioresour. Bioprocess.*, vol. 5, no. 1, p. 30, Dec. 2018, doi: 10.1186/s40643-018-0217-5.

[35] H. Fernández-Llamosas, L. Castro, M. L. Blázquez, E. Díaz, and M. Carmona, "Biosynthesis of selenium nanoparticles by Azoarcus sp. CIB," *Microb. Cell Factories*, vol. 15, no. 1, p. 109, Dec. 2016, doi: 10.1186/s12934-016-0510-y.

[36] S. Lampis, E. Zonaro, C. Bertolini, P. Bernardi, C. S. Butler, and G. Vallini, "Delayed formation of zero-valent selenium nanoparticles by Bacillus mycoides SeITE01 as a consequence of selenite reduction under aerobic conditions," *Microb. Cell Factories*, vol. 13, no. 1, p. 35, 2014, doi: 10.1186/1475-2859-13-35.

[37] H. G. Hussein, E.-S. R. El-Sayed, N. A. Younis, A. E. H. A. Hamdy, and S. M. Easa, "Harnessing endophytic fungi for biosynthesis of selenium nanoparticles and exploring their bioactivities," *AMB Express*, vol. 12, no. 1, p. 68, Dec. 2022, doi: 10.1186/s13568-022-01408-8.

[38] X. Liang *et al.*, "Fungal formation of selenium and tellurium nanoparticles," *Appl. Microbiol. Biotechnol.*, vol. 103, no. 17, pp. 7241–7259, Sept. 2019, doi: 10.1007/s00253-019-09995-6.

[39] S. Acharya, S. Nithyananthan, and C. Thirunavukkarasu, "Selenium Nanoparticles Show Anticancer Activity Through Regulation of HIF-1α and HIF-2α Under Hypoxic Condition in Liver Cancer Cells," *DNA Cell Biol.*, vol. 42, no. 7, pp. 433–444, July 2023, doi: 10.1089/dna.2023.0099.

[40] A. Puri and S. Patil, "Biogenic Synthesis of Selenium Nanoparticles using Diospyros montana Bark Extract: Characterization, Antioxidant, Antibacterial, and Antiproliferative Activity," *Biosci. Biotechnol. Res. Asia*, vol. 19, no. 2, pp. 423–441, June 2022, doi: 10.13005/bbra/2997.

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

[41] N. Golub *et al.*, "Phyto-Assisted Synthesis of Nanoselenium–Surface Modification and Stabilization by Polyphenols and Pectins Derived from Agricultural Wastes," *Foods*, vol. 12, no. 5, p. 1117, Mar. 2023, doi: 10.3390/foods12051117.

[42] M. K. Y. Soliman, M. A.-A. Amin, A. I. Nowwar, M. H. Hendy, and S. S. Salem, "Green synthesis of selenium nanoparticles from Cassia javanica flowers extract and their medical and agricultural applications," *Sci. Rep.*, vol. 14, no. 1, p. 26775, Nov. 2024, doi: 10.1038/s41598-024-77353-2.

[43] S. Mourdikoudis, R. M. Pallares, and N. T. K. Thanh, "Characterization techniques for nanoparticles: comparison and complementarity upon studying nanoparticle properties," *Nanoscale*, vol. 10, no. 27, pp. 12871–12934, 2018, doi: 10.1039/C8NR02278J.

[44] C. Mellinas, A. Jiménez, and M. D. C. Garrigós, "Microwave-Assisted Green Synthesis and Antioxidant Activity of Selenium Nanoparticles Using Theobroma cacao L. Bean Shell Extract," *Molecules*, vol. 24, no. 22, p. 4048, Nov. 2019, doi: 10.3390/molecules24224048.

[45] K. Pyrzynska, "Plant Extracts for Production of Functionalized Selenium Nanoparticles," *Materials*, vol. 17, no. 15, p. 3748, July 2024, doi: 10.3390/ma17153748.

[46] K. Pyrzynska, "Plant Extracts for Production of Functionalized Selenium Nanoparticles," *Materials*, vol. 17, no. 15, p. 3748, July 2024, doi: 10.3390/ma17153748.

[47] K. Pyrzynska, "Plant Extracts for Production of Functionalized Selenium Nanoparticles," *Materials*, vol. 17, no. 15, p. 3748, July 2024, doi: 10.3390/ma17153748.

[48] M. K. Y. Soliman, M. A.-A. Amin, A. I. Nowwar, M. H. Hendy, and S. S. Salem, "Green synthesis of selenium nanoparticles from Cassia javanica flowers extract and their medical and agricultural applications," *Sci. Rep.*, vol. 14, no. 1, p. 26775, Nov. 2024, doi: 10.1038/s41598-024-77353-2.

[49] S. S. Salem and A. Husen, "Effect of engineered nanomaterials on soil microbiomes and their association with crop growth and production," in *Engineered Nanomaterials for Sustainable Agricultural Production, Soil Improvement and Stress Management*, Elsevier, 2023, pp. 311–336. doi: 10.1016/B978-0-323-91933-3.00010-6.

[50] A. Husen and K. S. Siddiqi, "Plants and microbes assisted selenium nanoparticles: characterization and application".

[51] J. J. O. Garza-García *et al.*, "Selenium nanoparticles based on Amphipterygium glaucum extract with antibacterial, antioxidant, and plant biostimulant properties," *J. Nanobiotechnology*, vol. 21, no. 1, p. 252, Aug. 2023, doi: 10.1186/s12951-023-02027-6.

[52] B. K. Ndwandwe, S. P. Malinga, E. Kayitesi, and B. C. Dlamini, "Advances in green synthesis of selenium nanoparticles and their application in food packaging," *Int. J. Food Sci. Technol.*, vol. 56, no. 6, pp. 2640–2650, June 2021, doi: 10.1111/ijfs.14916.

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

[53] C. Ferro, H. F. Florindo, and H. A. Santos, "Selenium Nanoparticles for Biomedical Applications: From Development and Characterization to Therapeutics," *Adv. Healthc. Mater.*, vol. 10, no. 16, p. 2100598, Aug. 2021, doi: 10.1002/adhm.202100598.

[54] M. J. Iqbal *et al.*, "Interplay of oxidative stress, cellular communication and signaling pathways in cancer," *Cell Commun. Signal.*, vol. 22, no. 1, p. 7, Jan. 2024, doi: 10.1186/s12964-023-01398-5.

[55] A. D. A. El-Magid, M. A. Younes, and O. M. A. El-Hamid, "The Apoptotic Effects of Silver Nano-Particles and Spirulina Extract on Experimentally Induced Prostatic Cancer in Rats," *Pharm. Chem. J.*, vol. 58, no. 10, pp. 1475–1482, Jan. 2025, doi: 10.1007/s11094-025-03298-z.

[56] C. Zhu *et al.*, "Selenium nanoparticles decorated with Ulva lactuca polysaccharide potentially attenuate colitis by inhibiting NF-κB mediated hyper inflammation," *J. Nanobiotechnology*, vol. 15, no. 1, p. 20, Dec. 2017, doi: 10.1186/s12951-017-0252-y.

[57] M. Gharbavi, M. Mousavi, M. Pour-Karim, M. Tavakolizadeh, and A. Sharafi, "Biogenic and facile synthesis of selenium nanoparticles using *Vaccinium arctostaphylos* L. fruit extract and anticancer activity against in vitro model of breast cancer," *Cell Biol. Int.*, vol. 46, no. 10, pp. 1612–1624, Oct. 2022, doi: 10.1002/cbin.11852.

[58] B. A. Ali, R. M. Allam, M. S. Hasanin, and A. A. Hassabo, "Biosynthesis of selenium nanoparticles as a potential therapeutic agent in breast cancer: G2/M arrest and apoptosis induction," *Toxicol. Rep.*, vol. 13, p. 101792, Dec. 2024, doi: 10.1016/j.toxrep.2024.101792.

[59] N. F. Fahmy, M. M. Abdel-Kareem, H. A. Ahmed, M. Z. Helmy, and E. A.-R. Mahmoud, "Evaluation of the antibacterial and antibiofilm effect of mycosynthesized silver and selenium nanoparticles and their synergistic effect with antibiotics on nosocomial bacteria," *Microb. Cell Factories*, vol. 24, no. 1, p. 6, Jan. 2025, doi: 10.1186/s12934-024-02604-w.

[60] S. Sampath, V. Sunderam, M. Manjusha, Z. Dlamini, and A. V. Lawrance, "Selenium Nanoparticles: A Comprehensive Examination of Synthesis Techniques and Their Diverse Applications in Medical Research and Toxicology Studies," *Molecules*, vol. 29, no. 4, p. 801, Feb. 2024, doi: 10.3390/molecules29040801.

[61] E. O. Mikhailova, "Selenium Nanoparticles: Green Synthesis and Biomedical Application," *Molecules*, vol. 28, no. 24, p. 8125, Dec. 2023, doi: 10.3390/molecules28248125.

[62] S. H. Nile *et al.*, "Nano-priming as emerging seed priming technology for sustainable agriculture—recent developments and future perspectives," *J. Nanobiotechnology*, vol. 20, no. 1, p. 254, Dec. 2022, doi: 10.1186/s12951-022-01423-8.

[63] H. G. Hussein, E.-S. R. El-Sayed, N. A. Younis, A. E. H. A. Hamdy, and S. M. Easa, "Harnessing endophytic fungi for biosynthesis of selenium nanoparticles and exploring their bioactivities," *AMB Express*, vol. 12, no. 1, p. 68, Dec. 2022, doi: 10.1186/s13568-022-01408-8.

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

[64] K. Vrandečić *et al.*, "Antifungal activities of silver and selenium nanoparticles stabilized with different surface coating agents," *Pest Manag. Sci.*, vol. 76, no. 6, pp. 2021–2029, June 2020, doi: 10.1002/ps.5735.

[65] M. K. Y. Soliman, M. A.-A. Amin, A. I. Nowwar, M. H. Hendy, and S. S. Salem, "Green synthesis of selenium nanoparticles from Cassia javanica flowers extract and their medical and agricultural applications," *Sci. Rep.*, vol. 14, no. 1, p. 26775, Nov. 2024, doi: 10.1038/s41598-024-77353-2.

[66] A. Fouda *et al.*, "Antimicrobial, Antiviral, and In-Vitro Cytotoxicity and Mosquitocidal Activities of Portulaca oleracea-Based Green Synthesis of Selenium Nanoparticles," *J. Funct. Biomater.*, vol. 13, no. 3, p. 157, Sept. 2022, doi: 10.3390/jfb13030157.

[67] M. A. Hawsah, R. Abdel-Gaber, S. Al-Quraishy, H. M. A. Aljawdah, S. N. Maodaa, and E. Al-Shaebi, "Green synthesis of selenium nanoparticles using Azadirachta indica leaves extract: evaluation of anthelmintic and biocompatibility potential," *Food Sci. Technol.*, vol. 43, Apr. 2023, doi: 10.5327/fst.13223.

[68] K. J. Way, N. Katai, and G. L. King, "Protein kinase C and the development of diabetic vascular complications," *Diabet. Med.*, vol. 18, no. 12, pp. 945–959, Dec. 2001, doi: 10.1046/j.0742-3071.2001.00638.x.

[69] S. A. Abdulmalek and M. Balbaa, "Synergistic effect of nano-selenium and metformin on type 2 diabetic rat model: Diabetic complications alleviation through insulin sensitivity, oxidative mediators and inflammatory markers," *PLOS ONE*, vol. 14, no. 8, p. e0220779, Aug. 2019, doi: 10.1371/journal.pone.0220779.

[70] M. I. Alghonaim, S. A. Alsalamah, Y. Ali, and T. M. Abdelghany, "Green mediator for selenium nanoparticles synthesis with antimicrobial activity and plant biostimulant properties under heavy metal stress," *BioResources*, vol. 19, no. 1, pp. 898–916, Dec. 2023, doi: 10.15376/biores.19.1.898-916.

[71] A. Kumar *et al.*, "Nanopriming with phytofabricated selenium nanoparticles alleviates arsenite-induced oxidative stress in Spinacia oleracea L," *Environ. Sci. Pollut. Res.*, Oct. 2024, doi: 10.1007/s11356-024-35183-9.

[72] M. G. Hassan, M. T. Hawwa, D. M. Baraka, H. M. El-Shora, and A. A. Hamed, "Biogenic selenium nanoparticles and selenium/chitosan-Nanoconjugate biosynthesized by Streptomyces parvulus MAR4 with antimicrobial and anticancer potential," *BMC Microbiol.*, vol. 24, no. 1, p. 21, Jan. 2024, doi: 10.1186/s12866-023-03171-7.

[73] A. M. El-Badri *et al.*, "Comparative efficacy of bio-selenium nanoparticles and sodium selenite on morpho-physiochemical attributes under normal and salt stress conditions, besides selenium detoxification pathways in Brassica napus L.," *J. Nanobiotechnology*, vol. 20, no. 1, p. 163, Dec. 2022, doi: 10.1186/s12951-022-01370-4.

[74] I. Bano, S. Skalickova, S. Arbab, L. Urbankova, and P. Horky, "Toxicological effects of nanoselenium in animals," *J. Anim. Sci. Biotechnol.*, vol. 13, no. 1, p. 72, Dec. 2022, doi: 10.1186/s40104-022-00722-2.

[75] H. Wang *et al.*, "Prooxidation and Cytotoxicity of Selenium Nanoparticles at Nonlethal Level in Sprague-Dawley Rats and Buffalo Rat Liver Cells," *Oxid. Med. Cell. Longev.*, vol. 2020, pp. 1–12, Aug. 2020, doi: 10.1155/2020/7680276.

Online ISSN 3007-3197
Print ISSN 3007-3189

[76] Z. Wang *et al.*, "Optimization of fermentation parameters to improve the biosynthesis of selenium nanoparticles by Bacillus licheniformis F1 and its comprehensive application," *BMC Microbiol.*, vol. 24, no. 1, p. 271, July 2024, doi: 10.1186/s12866-024-03410-5.

[77] B. K. Ndwandwe, S. P. Malinga, E. Kayitesi, and B. C. Dlamini, "Advances in green synthesis of selenium nanoparticles and their application in food packaging," *Int. J. Food Sci. Technol.*, vol. 56, no. 6, pp. 2640–2650, June 2021, doi: 10.1111/ijfs.14916.