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Review article

ECOLOGICAL EFFECTS AND ENVIRONMENTAL FATE OF SILVER NANOPARTICLES IN SOIL AND IN THE WATER ECOSYSTEM: A REVIEW

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ABSTRACT

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Silver nanoparticles, which are appreciated due to their increased antibacterial, catalytic and conductive functions, are commonly employed in medical kits, cloths, cosmetics, and water filters, but their release through wastewater, biosolids, and runoff is highly dangerous as there is no regulation of their emission and transformation, such as sulfidation, aggregation, and dissolution. In soil ecosystems, AgNPs react with pH, redox conditions, organic matter, and clay, and sulfidation to Ag_2S causes short-term bioavailability to decrease but increases persistence; they disrupt microbial communities, inhibit nitrogen-fixing bacteria (e.g., Rhizobium), mycorrhizal fungi, and enzyme activities, decrease soil fertility, nutrient cycling, and plant-microbe symbiosis and cause oxidative stress in earthworms. Aquatic systems facilitate AgNP disaggregation, sedimentation, and ion release driven by organic matter and ions and cause toxicity at all trophic levels: algae experience the inhibition of photosynthesis and ROS damage, zooplankton feeding problems, and fish experience bioaccumulation, neurotoxicity and reproductive problems. Ag^+ ion release leading to protein/DNA damage, Oxidative stress due to ROS, membrane peroxidation, quorum sensing disruption and systemic changes in stress, detoxification and metabolism pathways confirmed by omics is a subset of the toxicity mechanisms. Though the water body information is plentiful, soil research is still very limited; gaps still exist in long-term low dose field effects and co-contamination. The research in the future recommends mesocosm/field testing, model dynamic transformation, and the safer design of nanoparticles to guide the risk analysis and sustainable management.

KEYWORDS: Silver nanoparticles; Environmental fate; Ecotoxicology; Aquatic ecosystems; Soil ecosystems.

1. INTRODUCTION

Nanotechnology has enabled the production of nanoparticles of silver (AgNPs) that exhibit enhanced physical, chemical, and biological characteristics that exceed those of bulk silver (Wang *et al*., 2018). Nano-sized materials are used to enhance catalytic activity, antibacterial properties, and electrical conduction, thereby expanding their applications in medical kits, antimicrobial protection, wound dressings, textiles, water filters, cosmetics, and packaging materials (Ghobashy *et al*., 2021). These applications utilize the microbial membrane-disrupting properties of AgNPs against microbial cells, making them invaluable in infection control and hygiene management (Sharma *et al*., 2019). Despite the rapid expansion of AgNP production due to the expanding consumer market for nano-enabled products, environmental risk assessments and regulatory measures have not kept pace (Khan *et al*., 2023). Therefore, although the usefulness remains unquestionable, widespread, unregulated use of AgNPs requires a simultaneous assessment of their ecological and long-term environmental consequences (Dang *et al*., 2021).

AgNPs enter the environment mainly via wastewater discharge, leaching out of landfills, and the surface runoff of agricultural soils treated with nano-enabled agrochemicals (Dodds *et al.,* 2021). Once liberated, silver nanoparticles are too small to settle due to their colloidal

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nature and may remain suspended in water bodies or within permeable soil matrices, where they may undergo intricate transformation processes (León-Silva *et al*., 2016). Research indicated that traditional wastewater treatment facilities cannot effectively eliminate nanoparticles, leading to their buildup in sewage sludge or release into natural water sources (McGee, 2020). AgNPs present in bio solids are often used as fertilizers in agricultural environments, where they have direct contact with soil biota/crops (Arienzo & Ferrara, 2022; Asad *et al.,* 2025).

Once in environmental compartments, AgNPs do not remain chemically stable; their properties are altered due to pH, redox potential, organic matter, and ionic strength (Khan & Akram, 2020). Nanoparticle contamination is a major concern for soil ecosystems, which are microbial diverse systems, and are indispensable to global nutrient cycling (Tangaa *et al*., 2016). AgNPs exposure may also inhibit symbiosis plant-microbe by inhibiting nitrogen-fixing bacteria and mycorrhizal fungi (Rajput *et al*., 2020). Research has reported a lowering of enzymatic activity, low microbial respiration, and changes in the turnover of carbon and nitrogen in the soil after exposure to AgNP . Such disturbances reduce not only the fertility of the soil but also above-ground productivity and biodiversity (Jahan *et al*., 2017). Additionally, plant roots can absorb and transfer AgNPs to plant tissues above ground, where they may proceed into the food chain may causing further damage to herbivores and even human beings (Du *et al*., 2018). Species that are detritivores, such as earthworms, are key in soil aeration and decomposition of organic matter, and evidence has been found that there are oxidative stress, stunted growth, and reproductive abnormalities in these organisms when they ingest AgNPs, thus indicating larger repercussions at the population level (Kalantzi *et al*., 2019).

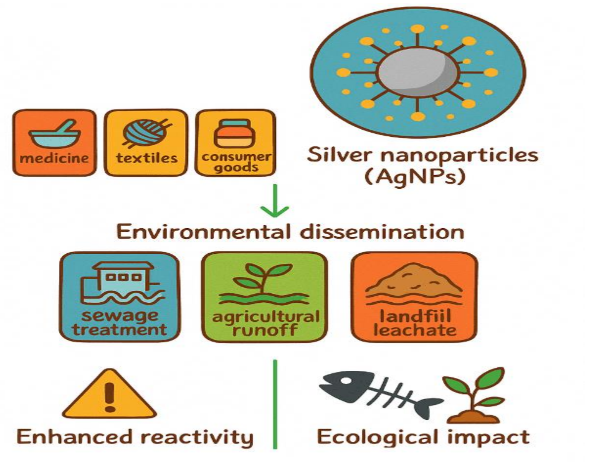

Figure 1: Summary of the industrial uses, the environmental exposure pathways, and biological hazards of AgNPs.

AgNPs in soil undergo sulfidation, aggregation, and complexation with organic matter, which affect microbial activity, plant health, and nutrient cycling. By contrast, aquatic systems facilitate dissolution, photoreduction, and ion release, which contribute to oxidative stress and bioaccumulation and can alter aquatic food webs. Although data on aquatic toxicology are sufficient, studies on soil are relatively narrow in scope and duration. It is essential to recognize that transformation pathways and vulnerabilities to the ecological environment vary between these settings, underscoring the necessity to tailor risk assessment to each specific situation and adopt sustainable methods for nanoparticle management (Padhye *et al*., 2023).

PRISMA-Guided Systematic Review:

An extensive and systematic literature review was done according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (https://prisma-statement.org/) protocol to provide methodological soundness and transparency. The search protocol targeted three of the largest academic databases, Web of Science (https://www.webofscience.com/), Scopus (https://www.scopus.com/), and PubMed (https://pubchem.ncbi.nlm.nih.gov/), to identify as many inter-disciplinary investigations as possible on the environmental fate of AgNPs. Research works that focused on environmental exposure pathways, trophic relationships, bacterial responses, and toxicological effects in non-human beings were given a higher priority (Kurwadkar *et al*., 2015). Articles were, in turn, not included when they paid attention to medical applications, synthetic protocols, or in vitro mammalian toxicology, and did not carry the ecological element. The removal of duplicate records and non-peer-reviewed (opinion pieces, conference abstracts, etc.) sources were also provided through additional filtering (Buffet *et al*., 2014). By using these criteria of inclusion and exclusion, 162 peer-reviewed articles published between the years 2010 and 2025 were found appropriate to be subject to a deeper level of analysis. The combination of these studies covers a variety of geographic areas, experimental geometry, and environmental conditions, which provides a solid background on assessing trends in pattern AgNP transformation, exposure pathways, and ecological risk exposure in terrestrial and aquatic environments (Akhter *et al*., 2024).

Ag NPs Environmental Fate:

AgNPs' fate in the environment depends on their size, surface coatings, and shape, and exogenous environmental factors, including pH, redox conditions, ionic strengths, and organic matter contents (Li et al., 2020). In the environment, AgNPs have been shown to exhibit dynamic transformations involving aggregation, dissolution to Ag^{+} ions, sulfidation, and complexation with natural ligands (Furtado et al., 2015). AgNPs persist in soil, affecting microbes and nutrient cycling, while in water, they remain bioavailable and toxic to aquatic life. While soil acts as a terminal sink, aquatic systems remain continuously polluted because wastewater treatment cannot fully remove AgNPs (Zhang et al., 2019).

AgNP in Soil Ecosystems:

AgNPs interact dynamically in soils, influenced by factors like pH, redox potential, organic matter, cation exchange capacity, and texture. Introduced via biosolids, agricultural inputs, or leachate, AgNPs can undergo sulfidation in sulfur-rich or anoxic environments, forming Ag_2S (Eivazi & Afrasiabi, 2018). Moreover, AgNPs

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spontaneously aggregate with clay minerals and become bound to humic and fulvic acids, which contribute to the surface adsorption of AgNPs, mostly at the topsoil roll (Grün *et al*., 2019). However, changes in pH, rainfall, or flooding can release AgNPs or ions, enabling vertical movement into subsoil, particularly in coarse-textured soils like sandy loams (Yang *et al*., 2017).

In addition to their geochemical activity, AgNPs produce a dramatic impact on the biological activity of soil microbiota and plant-microbe interaction (Kulikova, 2021). Oxidative dissolving of AgNPs leads to the liberation of silver ions (Ag^{1+}), which is an extremely active form that inhibits crucial essential activities in the beneficial soil organisms (Peyrot *et al*., 2014). The effects of Ag^{+} can be particularly toxic to nitrogen-fixing bacteria like Rhizobium and Azotobacter, with the presence of Ag^{+} shown to affect colony-forming units, activity of associated enzymes (e.g., nitrogenize), and symbiotic root nodulation (Cao *et al*., 2017). Such disruptions not only decrease nitrogen availability to plants, but also undermine larger soil fertility and ecosystem services (de Oca-Vásquez., *et al*., 2020). Moreover, AgNPs exposure has been known to decrease microbial carbon biomass and phosphatase responses, another way to express deteriorating microbial-mediated nutrient cycling (Zhang *et al*., 2020). Therefore, transformation processes can lead to changes in AgNP mobility, but the concomitant formation of detrimental species of silver introduces an ongoing ecological risk to the landscape food webs and crop production continuity (López-Mondéjar *et al*., 2020).

Figure 2 illustrates. AgNPs in soils undergo sulfidation to form Ag_2S, reducing short-term bioavailability while increasing long-term persistence (Zhang et al., 2020).

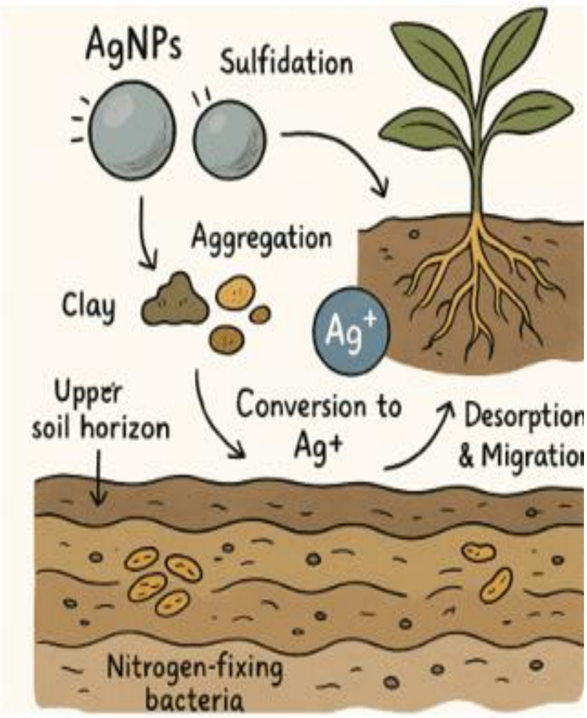

Figure 2: Diagrammatic representation of transformation, mobility, and the effect of AgNP in the soil ecosystem with important connections to soil components and microbial communities.

Aquatic Environments:

Aquatic environment forms a highly heterogeneous and chemically active environment where the fate and behavior of AgNPs are determined via a wide-ranging transformation mechanism. AgNPs are usually disaggregated in freshwater because of their interaction with divalent cations and natural organic matter, and such contacts decrease colloidal stability (Ellis *et al*., 2016). The results of this aggregation frequently sediment out of the water column and are laid down in sediments, particularly in lakes and slow-flowing rivers (Ottoni *et al*., 2020).

Figure 3 shows how AgNPs interact with dissolved organic carbon in water, leading to aggregation, agglomeration, and sedimentation, particularly in freshwater bodies (Sohn *et al*., 2015).

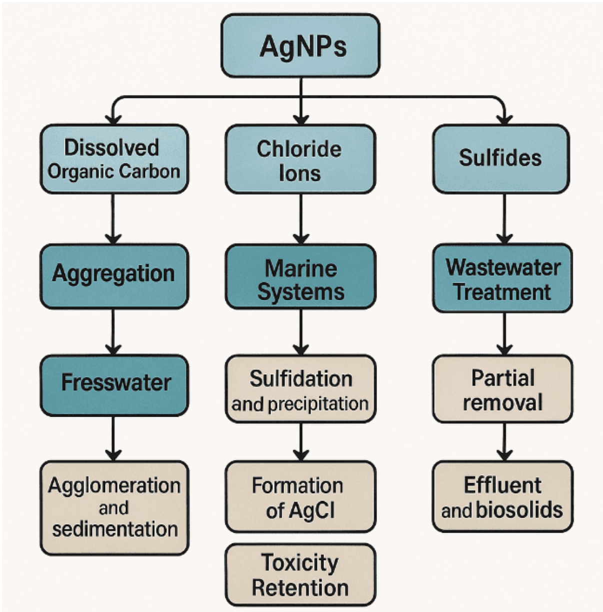

Figure 3: Major environmental routes, conversions, and fate of silver nanoparticles (AgNPs) in waters, which determined dissolved organic matter, chloride ions, and sulfides.

Ecotoxicological Impacts:

AgNPs exert ecotoxicological effects on several trophic levels through the destabilization of physiologic and biochemical mechanisms of affected organisms (Noga et al., 2023). Their small, reactive particles enter cells, causing oxidative stress, membrane damage, enzyme inhibition, and genotoxicity (Singh et al., 2022). AgNPs disrupt nutrient cycling, plant–microbe interactions, and microbial biomass by impairing nitrogen fixation and other key soil enzyme activities (Tonczyk et al., 2025). AgNPs and Ag^{+} disrupt algal photosynthesis, alter zooplankton feeding, and bioaccumulate in fish, causing inflammation, neurotoxicity, and reproductive failure (Aslam et al., 2024).

Organisms in soil:

Soil invertebrates, such as earthworms (*Eisenia fetida)* and springtails (*Folsomia candida*), are key bioindicators of soil health (Courtois, 2020). Environmentally relevant doses of AgNPs reduce growth, reproduction, and alter behavior (Oktarina, 2017). AgNPs enter soil invertebrates via integument penetration or

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ingestion, localizing in gut tissues and disrupting physiology (He *et al.*, 2016). They induce ROS production, causing oxidative stress, mitochondrial dysfunction, DNA damage, and protein impairment. In earthworms, this leads to gut epithelial disruption and lipid peroxidation (Grün *et al*., 2017).

In addition to the invertebrates, AgNPs, notably, the plant-root interaction microbes, also affect the beneficial microorganisms in the soil negatively. Mycorrhizal fungi, which aid the uptake of water and nutrients, and rhizobacteria, which aid in nitrogen fixation and the production of phytohormones, are very sensitive to exposure to nanoparticles (Tortella *et al*., 2020). The presence of AgNPs is especially highlighted in a multi-tiered ecotoxicological effect on soil biota, as shown in Figure 4.

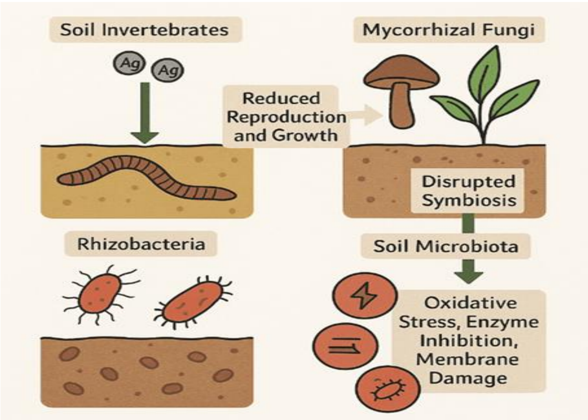

Figure 4: Mechanistic diagram of the effects of AgNP on soil organisms, including effects on invertebrates, mycorrhizal fungi, rhizobacteria, and microbial community.

Aquatic life:

Aquatic organisms exhibit a pronounced susceptibility to the toxic effects of AgNPs, with toxicity pathways strongly influenced by particle size, concentration, and the mode of exposure (Chaachouay *et al.*, 2024). *Chlorella vulgaris* and similar algae are primary producers in aquatic systems, making them among the first things to be exposed to AgNPs (Kusi & Maier, 2022).

Exposed AgNPs adsorb to the algal cell surface, or cell wall, into which they enter, interfering with chloroplast action and thylakoid membrane integrity. This leads to the reduction of chlorophyll levels and a malfunction of photosystem II, with such a detrimental effect on photosynthetic efficiency (Lapresta-Fernández *et al.*, 2012; Al Sulivany *et al.*,2025). Reactive oxygen species (ROS) generation increases cellular stress in algae, leading to oxidative damage and reduced photosynthetic efficiency, thus weakening the aquatic food (Kwok *et al.*, 2012). Additionally, nanoparticle surface coatings such as citrate, polyethylene glycol, or polyvinylpyrrolidone strongly influence AgNP dissolution and cellular uptake, modulating algal toxicity (Kang *et al*., 2023).

Figure 5 presents the specific organism adverse pathways that occur because of the AgNP exposure to the aquatic life.

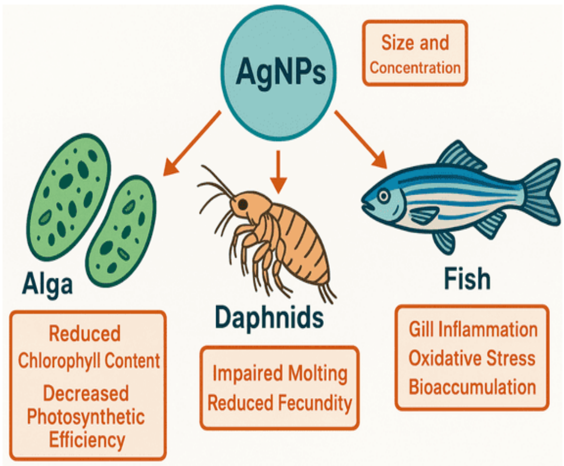

Figure 5: AgNP Toxicity mechanisms in aquatic biota approaches, representation in a schematic view with the point of defining organism-specific impacts, as well as the effects of particle size and surface chemistry.

Mechanisms of Toxicity:

The fundamental AgNP cellular toxicity mechanisms can be described using Figure 6. Ag^{+} release interferes with the structure of the protein and causes DNA to fragment, and the production of ROS causes oxidative stress and pervasive damage to the cell (De Matteis *et al.*, 2015).

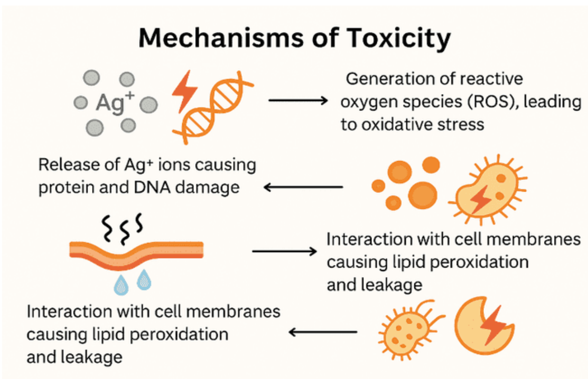

Figure 6: Mechanism of toxicity

Table 1: escribing the main ways in which AgNPs have cell toxicity, like, release of ions, the production of ROS, the disruption of membranes, and the disruption of microbes.

Mechanism Title	Description	Biological Implications	Ref.
Ag^{+} Ion Release Causing Protein and DNA Damage	AgNPs undergo partial dissolution under oxidative or acidic conditions, releasing Ag^{+} ions. These ions bind to thiol groups in cysteine-rich proteins, leading to denaturation, and interact with DNA, causing strand breaks.	Genotoxicity, impaired protein function, apoptosis, and mutation risk	(De Matteis *et al.*, 2015)

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ROS Generation and Oxidative Stress	AgNPs catalyze the formation of ROS such as superoxide, hydrogen peroxide, and hydroxyl radicals. These overwhelm cellular antioxidants, leading to lipid peroxidation, protein oxidation, and mitochondrial dysfunction.	Redox imbalance, inflammation, mitochondrial damage, and chronic toxicity	(Flores-Lopez *et al.*, 2019)
Membrane Interaction Causing Lipid Peroxidation and Leakage	AgNPs adhere to phospholipid membranes, disrupting their structure. Lipid peroxidation leads to membrane destabilization, ion leakage, and osmotic imbalance, often triggering necrotic or apoptotic cell death.	Cell lysis, impaired homeostasis, necrosis, or apoptosis initiation	(Paciorek *et al.*, 2020)
Disruption of Microbial Quorum Sensing and Enzymatic Pathways	AgNPs disrupt bacterial communication by degrading or blocking signaling molecules, suppressing biofilm formation and gene expression. Ag^+ ions inhibit key enzymes involved in energy and nitrogen metabolism.	Suppressed microbial activity, biofilm inhibition, nutrient cycle collapse	(Gomez-Gomez *et al.*, 2019)
Omics-Based Evidence of Systemic Disruption	Omics studies reveal widespread gene expression changes linked to stress, detoxification, and inflammation. Proteomics and metabolomics confirm disruption in cytoskeletal proteins and energy/lipid metabolism.	Whole-organism dysfunction, prolonged stress responses, impaired metabolic regulation	(Abdelkader *et al.*, 2023)

Ag ions leaking into Cells, resulting in Damage to Proteins and DNA:

Silver ions (Ag^+) release due to one of the most basic mechanisms of AgNP toxicity has highly characteristic biochemical activities AgNPs can also easily transform into a partial dissolution form to release Ag^+-agents, especially in oxidation conditions or acidic environments. The effects of silver ion (Ag^+) infiltration into cells are illustrated in Figure 7. Once inside, Ag^+ binds to thiol-containing proteins and nucleic acids, disrupting their structural integrity (Li *et al.*, 2017).

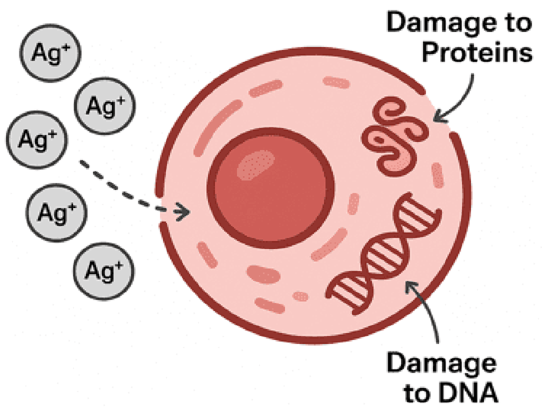

Figure 7: Oxidative stress is linked to intracellular Ag+ infiltration, which damages proteins and DNA as presented.

Reactive Oxygen Species production and oxidative stress:

It is also known that AgNPs can catalyze the generation of ROS, including superoxide radicals, hydrogen peroxide, and hydroxyl radicals. This occurs by redox cycling at the nanoparticle surface or as secondary responses of cells to Ag+. The production of ROS throws the intercellular redox balance out of control and overburdens antioxidant countermeasures like glutathione, superoxide dismutase, and catalase (Saini et al., 2016). This leads to widespread cellular damage due to oxidative stress, such as the peroxidation of lipids, carbonylation of proteins, and oxidative changes in nucleic acids (He, 2013).

Interaction of AgNPs with Cell Membranes leading to Lipid Peroxidation and Loss of Membrane Integrity:

Another important mechanism of AgNPs is direct interactions with cell membranes. Due to their small size and high surface area, AgNPs readily interact with phospholipid membranes, increasing permeability and losing selective ion gradients (Ahmed et al., 2018; Paciorek et al., 2020). These interactions promote lipid peroxidation and membrane destabilization, leading to osmotic imbalance, enzyme inhibition, and ultimately necrotic or apoptotic cell death (Nayak et al., 2016). The interaction of nanoparticles or reactive oxygen species with the lipid bilayer of the cell membrane induces peroxidation of the lipid (Figure 8).

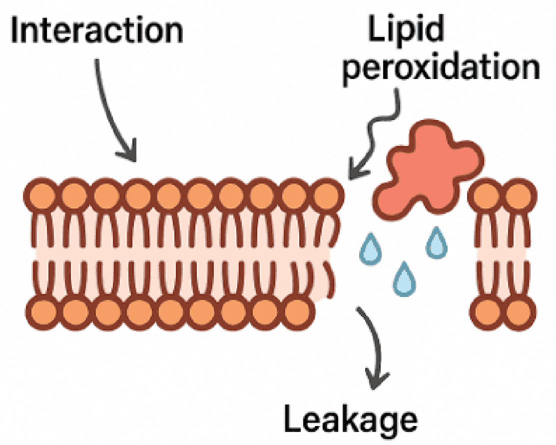

Figure 8: Lipid peroxidation produces disruption of the cell membranes, resulting in structural damage and intracellular leakage.

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Influence on Bacterial quorum sensing and enzymatic pathways:

AgNPs also affect metabolism and intercellular communication, besides compromising the cellular structure in the microbial system (Awadelkareem et al., 2023). The chemical communication chain known as quorum sensing (QS), through which bacteria synchronize group behavior like biofilm production, aggressiveness, and sharing of resources, is highly susceptible to the interference of AgNP (Shah et al., 2019). AgNPs may have the ability to suppress QS-controlled gene expression by breaking down signal molecules (e.g., acyl homoserine lactones) or attaching to receptor sites (Wolska et al., 2017). Furthermore, the presence of released Ag^{+} ions into the nanoparticles distorts important enzyme reactions, including the ATP production process, nitrogen fixation (e.g., nitrogenase activity), and dehydrogenase activity (Qadeer et al., 2024). The effect of this disturbance ultimately reduces bacterial growth and survival (Khusro et al., 2023).

Figure 9 reveals the spatial and functional division in bacterial cells between quorum-sensing mechanisms and enzymatic pathways (Peixoto et al., 2022).

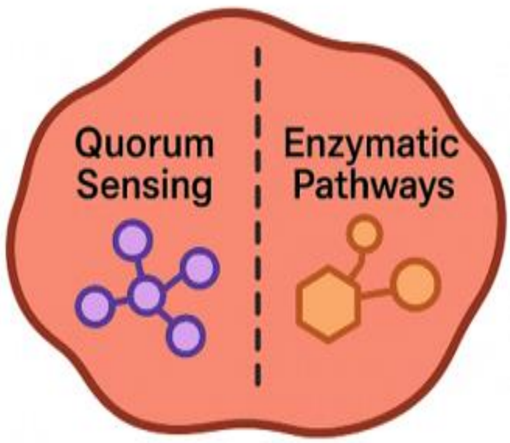

Figure 9: The division of quorum-sensing processes and enzymatic processes means that the behavior and metabolism of bacteria can be carefully regulated.

Evidence of Systemic Disruption by Omics:

Recent developments in high-throughput omics technologies like transcriptomics, proteomics, and metabolomics have offered molecular-scale insights into systems-level responses of organisms to AgNPs exposure (Aragoneses-Cazorla et al., 2022). Research indicates that transcriptome profiles are altered, involving oxidative stress reactions, metal detoxification (e.g., metallothioneins), inflammation, and apoptotic signaling pathways (Anh et al., 2023). As an example, upregulation of stress-related genes (HSP70, GPX) could reflect successful efforts in adapting cells, whereas downregulation of genes related to mitochondrial respiration and cell division reflects intrinsic toxicity (Gavin, 2016). The proteomic studies demonstrate that the expression of cytoskeleton and membrane proteins has changed, whereas in the metabolomics, alterations were observed in amino acid, lipid, and energy metabolism (Qi et al., 2024). Such multiple-layered perturbations highlight a systemic cellular response to AgNP exposure, indicating that the toxicity is not limited to a few specific pathways but coordinated stress response in a biological system as a whole (Li et al., 2024).

The combined study of omics layers, genomics, transcriptomics, proteomics, and metabolomics is offered in Figure 10 to identify systemic biological perturbations (Andrejević et al., 2023).

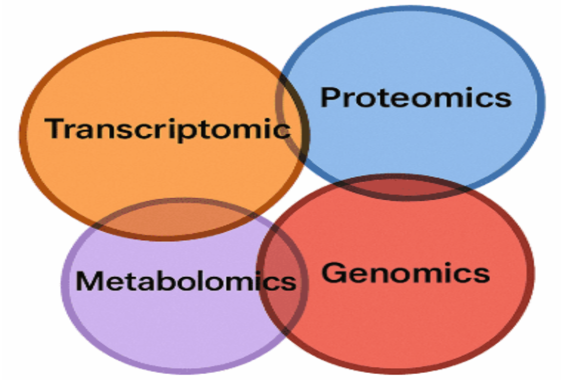

Figure 10: Multi-omics levels unmask systemic molecular perturbations in terms of their genomic, transcriptomic, proteomic, and metabolomic aspects.

Future Research Directions:

To fill research gaps, AgNP studies should extend beyond the lab to mesocosm and field experiments, which simulate natural conditions and capture ecological interactions such as microbial responses, nutrient cycling, and trophic effect (Shaikh *et al.*, 2021). Such extensive validation plans will not only prove the environmental applicability of the previous results but will also help in elaborating regulatory guidance and risk assessment methods, which are based on the ecological reality (Jangid *et al.*, 2024). AgNPs is the examination of nanoparticle transformation processes occurring under the variable environmental conditions, particularly to the variation of redox potential, seasonal changes, and microbial activity (Xiao *et al.*, 2019). In dynamic ecosystems, AgNPs rarely remain in their original form; they continuously undergo oxidation, sulfidation, aggregation, or corona formation, often driven by microbial activity or environmental factors such as temperature fluctuations and photoperiod changes (Rajkuberan *et al.*, 2015). AgNP transformations can alter surface charge, reactivity, and bioavailability, affecting toxicity and environmental persistence (Chutrakulwong et al., 2024; Vivekanandhan et al., 2012). Laboratory microcosms combined with omics tools can clarify these changes and guide safer-by-design strategies (Yadav & Sahu, 2024).

CONCLUSION

AgNPs significantly impact both soil and aquatic ecosystems due to their small size, high surface activity, and ion release. They disrupt microbial diversity and enzyme functionality critical for nutrient cycling, affecting soil fertility and plant health. AgNP longevity is influenced by their interactions with soil components, which affect their mobility and bioavailability. In aquatic environments, AgNPs cause oxidative stress and alter trophic relationships, with toxicity often linked to the

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release of Ag+ ions. Bioaccumulation raises concerns for long-term ecosystem health, especially in nutrient-rich or slow-flowing waters. Current research reveals knowledge gaps related to long-term low-concentration exposure and interactions with co-contaminants, while most studies focus on short-term, single-species models. Lack of standardized methodologies hampers comparison and risk assessment efforts. Future approaches should combine laboratory, mesocosm, and field studies, utilizing advanced modeling and omics technologies to enhance understanding of AgNP effects, alongside prioritizing environmentally friendly synthesis and design strategies.

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Ethical Statement:

This article is a review based on previously published literature. It does not involve any experiments on humans or animals, and therefore, ethical approval was not required.

Author Contributions:

Conceptualization, A.U., M.J, and B.S.A.A.S.; literature review, A.U., R.Y., and M.J.; data analysis, M.A., I.U.M., and M.T.R.; writing original draft preparation, A.U. and I.U.M.; writing review and editing, R.M.F. and B.S.A.A.S.; supervision, B.S.A.A.S. All authors have read and agreed to the published version of the manuscript.

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