

ECOTOXICOLOGICAL IMPACT OF BIOINSPIRED SILVER NANOPARTICLES: A SHORT REVIEW

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ABSTRACT

The exponential progress of nanotechnology has garnered a huge technological and scientific interest due to its many uses in devices and functional materials. Owing to various attractive physicochemical properties, nanoparticles differ from bulk material, leading to the reaction with every component of the environment to a great extent. As a result, their production and release into the environment increase simultaneously. However, there is a deficiency of knowledge of the potential risk of nanoparticles because many researches are either in early stages or are technology-dependent. Very few frameworks with a globally unified policy are modeled around the environment and living organisms. A holistic way of addressing the potential risk of nanoparticles ought to be accounted for. Considering the fact, the objective of our studies is to assess the potential risk of biogenic nanoparticles in the environment. It also examines the state of the art in the future application of bioinspired AgNPs without any environmental risk. This critical review is based on literature. However, a pool of such discourses and their contextual evidence are rarely available in the literature. This review article describes the impact of bio-inspired silver nanoparticles on every component of the environment. This discourse also

focuses on the assessment of the toxicity of sustainable green synthesized AgNPs. It is centered on recent advances and future considerations for the application of AgNPs alongside the probable challenges associated with their use.

Keywords: *Bioinspired Nanoparticles, physicochemical property, ecotoxicity, environmental risk, risk assessment.*

Introduction:

In the last three decades, a huge expansion of nanotechnology has been creating intense curiosity, spreading novel application in myriad sectors and becoming pivotal in research. Among various types of nanoparticles, silver nanoparticles (AgNPs) are vastly used in medicinal biology, agricultural applications, and the industrial sector. The sustainable application of nanoparticles in the formulation of agrochemicals is responsible for revolution in agricultural fields by reducing the necessity of pesticides. These particles are also attributed to minimizing environmental stresses, controlling nutritional loss, improving crop yield, protecting plants from pathogens, and altering their life cycle patterns. Moreover, AgNPs help in the drug delivery system by treating cancer cells with little side effects. These particles also act as protective shields in food preservation and against ultraviolet radiation. AgNPs contribute to the diagnostic procedure and purification of heavy metals from wastewater.

To meet the increasing demand for nanoparticles, various chemical and physical synthesis processes like electrochemical reduction, microwave irradiation, heat-induced evaporation, etc, have been evolved. These methods are mostly energy-intensive, complicated, and expensive and release a large number of toxic byproducts into the environment. However, the green synthesis of nanoparticles has drawn popularity as an alternative to traditional methods, becoming economically beneficial, eco-friendly, and simple (Awasthi et al., 2022).

Due to the fast and wide progress of 'Nanotechnology' with huge production and diversity of nanomaterials application, there is important to concern about its biological effects, cellular interaction and toxicity for plants, animals and ecosystems. The ecotoxicological effect of AgNPs on

ecosystems is not clearly explained yet (Tsepina et al., 2024). Therefore, this article briefly overviewed the interaction of AgNPs at a molecular level with every component of the ecosystem for a long period. It is essential to explore the existing gap concerning the risk assessment of exposure to silver nanoparticles.

The swift commercialization of nanomaterials is anticipated to increase the release of silver nanoparticles into the environment, potentially posing a health risk to humans (Wong et al., 2023). AgNPs provide a dual-edged sword – they may be applied to mitigate environmental pollution, but they may also be responsible for toxicity to the environment. These particles manifest themselves in the ecosystem through several pathways –

- a) Intentionally anthropogenic silver nanoparticles
- b) Unintentionally, nanoparticles from industrial process
- c) Naturally generated nanomaterials

The process and trajectory of generation determine how nanoparticles affect biological things. Additionally, these are controlled by their physicochemical characteristics and environmental accumulation potential (Arora et al., 2024).

Around the world, ongoing research is attempting to minimize the toxicity level associated with nanoparticles. This chapter reviewed the eco-toxicity of plant-based AgNPs on the ecosystem. This chapter also delves into the direct interaction of AgNPs with living beings. To explore the impact of AgNPs on components of the environment, we elaborate on the detailed stability and potentiality of nanoparticles through this chapter. Future research should maintain a balance in the application of nanoparticles for the well-being of the ecosystem by several eco-friendly norms.

Positive Impact of silver nanoparticles on the environment:

Some characteristics, such as huge potential of reactivity and especially nanoscale (1-100 nanometers) dimension, high surface ratio to volume, etc, enable AgNPs to be suitable for

applications in catalysis, antimicrobial activity, drug delivery, and imaging (Cheng et al.,2023).

(1)As an antimicrobial agent:

Silver nanoparticles exhibit both broad-spectrum antimicrobial properties and synergistic effects in combination with certain antibiotics. The following steps are followed in proteomic mechanisms of antimicrobial action of AgNPs:

- Reactive Oxygen Species (ROS) production
- DNA damage
- bacterial cell rupture
- protein synthesis inhibition

The application of AgNPs in new therapeutics to combat bacterial resistance represents a substantial advancement in Nanotechnology.' Current applications of nanomedicine benefit patients in terms of safety, infection control, and efficacy.

(2)As an antibiofilm agent:

Bacteria in the planktonic state are dispersed in search of nutrients in the microenvironment in a community or attached to surfaces together, known as biofilm. In biofilm, bacteria can tolerate the harsh conditions by an extracellular polymeric matrix that helps in adhesion. These biofilms infect the surgical site of patients as well as cause a longer recovery time that increases treatment costs or sometimes results in death (Bajire et al.,2023)

As biofilm agents, AgNPs commercially act as a coating material of various medical substances like catheters, wound dressings, etc, to prevent the spreading of infection (Al-Sawarees et al., 2024). Three distinct steps are governed by AgNPs for controlling biofilm growths:

(a) AgNPs being charged interact with the surface of biofilm.

(b) AgNPs enter into the biofilm liable on the surface chemistry, charge, size, and concentration of nanoparticles

as well as the surface composition of biofilm.

(c) AgNPs subsequently penetrate the biofilm and engage with its various components. (Chauhan et al., 2023).

On the other hand, from the literature, bacterial resistance to AgNPs is also noted. Some mechanisms, such as chemical detoxification mechanisms, active efflux systems, etc., contribute to bacterial resistance to AgNPs. Bacterial resistance to AgNPs involves multiple strategies to counteract silver toxicity. Bacteria induce AgNP aggregation and reduce Ag^+ to Ag^0 , minimizing its reactivity. They prevent silver entry by modifying membrane permeability and expel Ag^+ ions via efflux pumps. Defense mechanisms are activated to neutralize toxicity while cell damage is repaired. Biofilm formation acts as a shield, surface charge alterations reduce silver binding, and stress responses enhance bacterial survival.

According to Li and Xu (2024), this mechanism involves a series of interrelated systems. When cells are exposed to sublethal concentrations of AgNPs, oxidative stress and damaged DNA trigger the development of bacterial resistance phenotypes.

(3) As a dye removal agent from wastewater:

The world is grappling with challenges related to the contamination of water with dyes. Recently, dyes have been universally recognized as carcinogenic substances, contributing to elevated BOD (Biological Oxygen Demand), reducing photosynthesis activity, hampering the growth of plants, and decreasing light penetration into aquatic ecosystems (Ardila-Leal et al., 2021). The bioinspired AgNPs exhibit remarkable catalytic properties in degrading dyes where NaBH_4 (Sodium hydroborate) is a reducing agent. In this process, electrons are moved from the borohydride anion (BH_4^-) to the dye molecules. This electron triggers the degradation of dyes by targeting the chromophore ring and making it colorless.

Negative Impact of Silver Nanoparticles on the Environment:

Up to a certain level, AgNPs are not regarded as toxic but beneficial in many aspects. Beyond the permissible limit, silver nanoparticles are regarded as a toxic compound to

the ecosystem, though the toxicity of AgNPs and Ag⁺ is not the same. The vast application of AgNPs raises the risk to the environment and the ecotoxicological effect on living organisms over the last decades. The toxicity level of AgNPs conditionally depends on the source of exposure, their highest level of accumulation in every taxon, and the biological community that consumes it. The Environmental Protection Agency (EPA) and the World Health Organization (WHO) have set the Maximum Contamination Limit (MCL) at 0.1 mg/L for silver. However, the Predicted Environmental Concentrations (PECs) of AgNPs typically fall within the range of 0.03- 0.08 mg/L. Moreover, the L(E) C50 value of AgNPs is 0.1mg/L, which makes it a deleterious toxic compound in the environment (Ihtisham et al., 2021). After being released into the environment, AgNPs either may be oxidized to generate a more reactive ionic form (Ag⁺) or are transformed into more toxic species like silver nitrate, silver chloride, etc. Ag of AgNPs can be converted into Ag₂S by a sulfidation reaction, while sulfide accelerates the aggregation of AgNPs and forms a chain-like structure.

Ecotoxicological impacts on animals:

The cytotoxicity of AgNPs leads to the generation of huge amounts of ROS, affecting the cytoskeleton, interfering with DNA repair enzymes, and inducing cell apoptosis (Figure 1). Amr et al. (2023) explained the cytotoxicity potential of AgNPs against human skin fibroblasts.

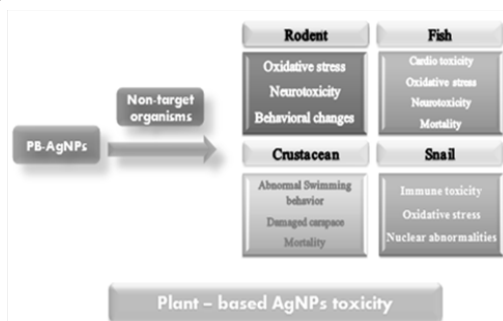


Figure 1: Ecotoxicity of plant-based AgNPs on animals.

- **On humans:**

The toxic effects of silver nanoparticles are multifaceted and include genotoxicity, cytotoxicity, and effects on the immune system. Therapeutic applications of AgNPs in the human body lead to the damage of erythrocytes (hemolysis, membrane damage, and agglutination). The systemic system can also be affected by deposited nanoparticles in the respiratory tract with the help of the phagocytosis process. Elfsmark et al. (2022) demonstrated that metal-based nanoparticles generate a huge amount of pro-inflammatory cytokines and ROS in epithelial cells of human lungs.

- **On fish:**

Studies indicate that exposure to AgNPs leads to a decline in the levels of essential amino acids, including L-histidine, L-isoleucine, and L-phenylalanine, in fish gills. This disruption in amino acid metabolism results in metabolic dysfunction and reduced energy production in the gills. AgNPs also disrupt the citrate cycle as well as energy production by altering the citric acid level. Marinho et al. (2021) observed that activities of acetylcholinesterase (AChE) in both the brain and muscle of zebrafish are substantially reduced by AgNPs. Exposure to AgNPs in adult zebrafish has been linked to hepatotoxicity, increased mortality, DNA damage, histopathological alterations in the gills, and nuclear abnormalities.

Ecotoxicological impacts of AgNPs on plants:

Mitochondria, chloroplasts, and peroxisomes are related to oxidative metabolic activity and electron flow that generate ROS in plant cells. The ecotoxicological impacts of AgNPs on plants are summarized in Table 1. These ROS alter membrane fluidity and permeability, lipid peroxidation, and bring difficulties in nutrient acquisition. In this way, after introducing into the plant cells, metal-based nanoparticles alter the plant metabolic process by affecting the intercellular organisms. Silver nanoparticles also damage plant cells and DNA, especially breaking DNA strands and causing chromosomal aberration.

Table 1: Summary of phytotoxic impacts of AgNPs in plants

Nanoparticles	Species Name	Ecotoxicological Impacts	References
Silver nanoparticles	Corbicula fluminea	Severe tissue damage induced oxidative stress imbalance antioxidant enzyme	
Activities(SOD, MDA, CAT)	Li et al., 2024		
	Oryza sativa	reduces the mitochondrial membrane potential	Ihtisham et al., 2021
	Pennisetum glaucum	induced antioxidative responses	Khan et al., 2020
	Arabidopsis thaliana	affected thylakoid membrane of chloroplasts	Kruszka et al., 2020
	Zea mays	induced activity of antioxidative enzyme reduction of plant growth	Yilmaz et al., 2021
	Stevia rebaudiana	induce in gene expressions of Kaurenoic Acid Hydroxylase (KAH) that leads to glycoside's biosynthesis	Ramezani et al., 2020
	Vicia faba	induced a series of changes on leaves like necrotic spot-on leaf, reduced photosynthetic rate, decreased photosynthetic pigment, induced non-photochemical quenching	Falco et al., 2020
	Prosopis juliflora	Reduce photochemical efficiency	Valdez-Salas et al., 2020

Perspectives:

- Conduct studies on the toxicokinetics of plant-based AgNPs in living organisms.
- Confirm the sustainable and safe application of AgNPs from one health perspective.
- Develop robust studies on the biomagnification and trophic transfer of AgNPs.
- Develop new clean technology to fruitfully decrease the ecological risk related to AgNPs.
- Determine various ecotoxicological matrices like Effective concentration (EC50), LC50, Lowest-Observed-Effect Concentration (LOEC), and No-Observed-Effect Concentration (NOEC) to accurately calculate the concentration for safe using of PB-AgNPs.

Conclusions:

The biological, chemical, and physical properties of nanoparticles make them demandable in every field of our day-to-day life. Nanoparticles maintain a life-cycle where chances exit to release in the environment at every stage. Despite having advantageous properties of bioinspired AgNPs, these nanoparticles are not exempted from ecotoxicity. Therefore, this bibliometric and systematic review provides a current understanding of potential risks in deliberately using AgNPs. The plant based AgNPs induced toxic impacts on non-target animals, and safe concentrations of these NPs for living organisms in the one health context should be accurately framed. A lot of advancement has been made in investigating ecotoxicity, but an integrated ecotoxicity assessment approach essentially needs to be developed to support the research on interactions between AgNPs and living organisms. Quantitatively structured-activity relationships, integrated biomarker responses, and read-across techniques are some effective tools of computational toxicology applications that will revolutionize the research on the ecotoxicity of silver nanoparticles in the future.

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