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Biogenic nanoparticles as multifunctional tools: From microplastic-driven atheroma insights to agricultural productivity and biofilm management

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Abstract
Biogenic nanoparticles, which are made from microorganisms and plant-derived biomolecules, are transforming sustainable nanotechnology by offering multifunctional and eco-friendly solutions for a range of industries. By removing hazardous chemicals and high energy requirements, these biologically produced nanoparticles outperform traditional chemical and physical synthesis methods, leading to enhanced biocompatibility and customized surface functions. Through quorum sensing interference, oxidative disruption, and extracellular matrix disintegration, their physicochemical plasticity contributes to creative biofilm management while enabling tailored treatments in agriculture that improve nutrient efficiency, resilience, and disease suppression. Additionally, new connections between environmental health and nanotechnology show potential in treating diseases caused by microplastics. Biogenic nanoparticles may have diagnostic, degradative, and therapeutic uses to reduce the dangers associated with microplastics, which are linked to the development of arterial plaque (atheroma). This review critically evaluates the safety, scalability, and environmental impact issues while thoroughly examining synthesis methods, structure-function correlations, and a wide range of applications. Biogenic nanoparticles are emerging as important tools to solve urgent issues in food systems, infectious disease control, and vascular illnesses connected to microplastics by combining nanobiotechnology, plant-microbe ecology, and biomedical science.

Keywords: Chhani, consumption, fuel-wood, households, Lanchaan

Introduction
The rapid development of nanotechnology has had a significant impact on a variety of fields, such as materials engineering, environmental science, medicine, and agriculture. Among the many methods for creating nanomaterials, biogenic synthesis which uses living things like bacteria, plants, and their metabolites has become a feasible, sustainable, and cost-effective substitute for conventional physical and chemical processes [1, 2]. The amazing enzymatic and metabolic capacities of microorganisms, such as bacteria, fungus, actinomycetes, and algae, enable the stability of nanoparticles and the reduction of metal ions in moderate, environmentally benign circumstances [3, 4]. Parallel to this, phytochemicals produced from plants work well as capping and reducing agents, producing stable nanoparticles with built-in biological activity. These biogenically produced nanoparticles are very relevant in a variety of multidisciplinary fields due to their exceptional biocompatibility, varied functional characteristics, and modifiable physicochemical features [5, 6].

Given the need to feed the world's growing population while causing the least amount of environmental damage, sustainable agriculture is one of the most potential uses of biogenic nanoparticles. By acting as nano-fertilizers, nanoherbicides, and nanofungicides, these nanoparticles improve nutrient bioavailability, inhibit phytopathogens, and lessen the need for artificial agrochemicals [7, 8]. Additionally, their inherent antibacterial properties and capacity to trigger plant defense systems lead to increased crop output and resistance. These developments support resource-efficient and ecologically responsible food production systems, which align with the goals of precision and sustainable agriculture.

Biogenic nanoparticles have great potential for regulating biofilms, which are intricate microbial assemblies encased in extracellular polymeric substances that the microorganisms manufacture on their own, in addition to agriculture [9, 10, 11]. Because of their increased resistance to antibiotics and disinfectants, biofilms present significant issues in industrial, medicinal, and water treatment settings [12, 13]. Through a variety of strategies, such as the production of reactive oxygen species, extracellular matrix penetration, and interference with microbial quorum sensing pathways, biogenic nanoparticles fight biofilms [14, 15]. These characteristics open up new avenues for reducing industrial biofouling, managing chronic illnesses, and protecting water quality.

Additionally, new research indicates a critical intersection between nanotechnology and the health risks associated with microplastics, particularly with regard to atheroma formation, which is the buildup of lipid-rich plaques in arterial walls linked to cardiovascular disease; ubiquitous microplastics accumulate in biological tissues and trigger inflammatory responses that may worsen atherogenesis; biogenic nanoparticles have the potential to be novel tools for detecting, capturing, degrading, or neutralizing microplastics, thereby reducing their detrimental health effects; and research into nanoparticle-microplastic interactions may reveal new therapeutic approaches to address vascular diseases associated with microplastics.

This thorough overview summarizes recent developments in the synthesis, characterisation, and multifunctional use of biogenic nanoparticles, with a focus on their uses in biofilm suppression, sustainable agriculture, and the management of microplastic-related atheroma [19, 20]. Important topics pertaining to environmental behavior, production scalability, safety of nanoparticles, and regulatory concerns are also covered. Through the integration of knowledge from environmental health, biomedical sciences, and nanobiotechnology, this work emphasizes the vital role of biogenic nanoparticles as adaptable agents ready to address some of the most pressing issues facing ecological sustainability, food security, and public health today [21, 22].

Mechanisms of Biogenic Nanoparticle Synthesis

Biogenic synthesis uses the biochemistry of microorganisms and plants to convert ionic precursors into nanoscale materials in mild conditions. Stabilizing biomolecules act as capping agents, providing durability and morphological control, while key metabolic mediators -enzymes like flavonoids, phenolic acids, and NADH-dependent reductases- drive electron transfer, nucleating metal atoms into functional nanostructures.

The process progresses through

1. **Initiation:** Enzymatic reduction to metallic zero-valent states occurs during ion adsorption or internalization [25].
2. **Growth:** Atomic deposition under control, directed by physicochemical microenvironments [26].
3. **Termination/Stabilization:** creation of organic corona through metabolites, proteins, and polysaccharides [27].

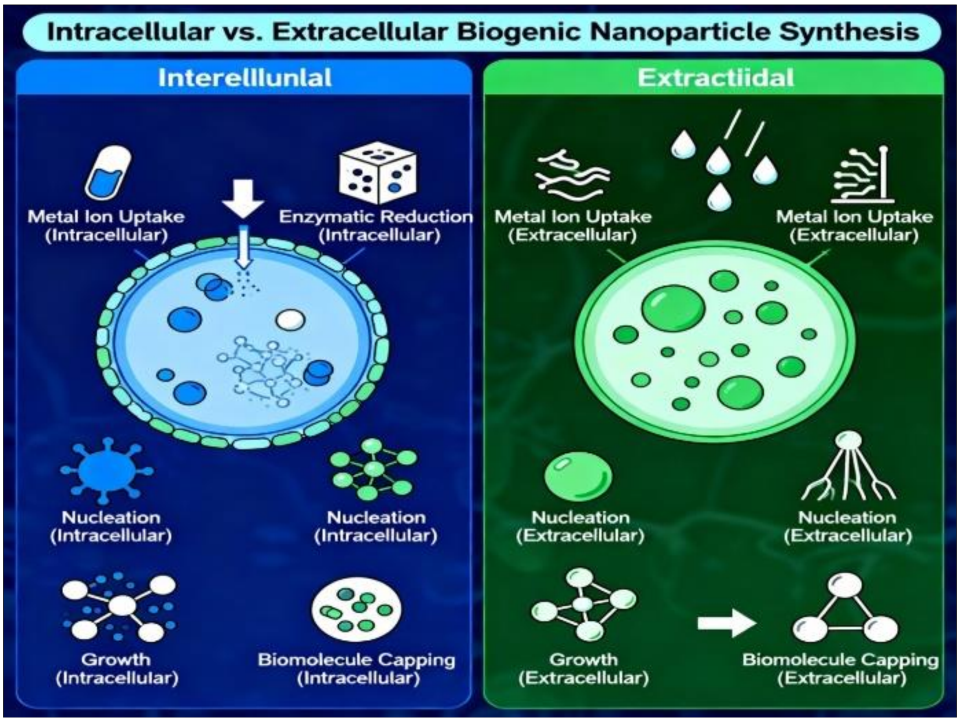

Fig 1: A comparative schematic of intracellular vs. extracellular synthesis, highlighting ion uptake, enzymatic reduction, and capping stages.

Applications in Sustainable Agriculture

Biogenic nanoparticles reduce reliance on chemical inputs, enhance stress tolerance, control microbial and insect pressures, and provide precise nutrient dosing. Through regulated release kinetics, nano-fertilizers, such biogenic ZnO and FeO, improve photosynthetic efficiency, soil-plant nutrient cycle, and nutrient bioavailability. By upsetting membranes and oxidative equilibria, silver and copper nanoparticles protect plants by inhibiting phytopathogens at microconcentrations [30]. Through phytohormonal modulation, pre-sowing seed priming with biogenic nanoparticles speeds up root-shoot growth and germination. To maintain ecological integrity, environmental stewardship necessitates toxicity studies that concentrate on interactions between particles, microbes, and soil as well as lifecycle effects.

Biofilm Inhibition and Control

Through modified microbial physiology and protective extracellular matrix, biofilms withstand traditional antimicrobials. Biofilms are repelled by biogenic nanoparticles through:

Preventive mechanisms: altering surface energy to interfere with quorum sensing signals and prevent initial microbial attachment [34].
Disruptive mechanisms: Penetrating extracellular polymeric substances (EPS), generating reactive oxygen species, degrading nucleic acids/proteins, and destabilizing cell membranes [35].
Activity is increased by functionalized nanoparticles; for example, coupling with DNase promotes the breakdown of EPS. Antibiotic combination treatments show a synergistic decrease in microbial burden [36]. Hygienic surface treatments in food processing and anti-biofouling coatings in water systems are examples of industrial and environmental uses.

Microplastic Interactions and Atheroma Implications

Their persistence in the vasculature highlights the urgent need for mitigation. Microplastics enter biological systems by ingestion, inhalation, and skin exposure, causing oxidative stress, endothelial dysfunction, and inflammatory cascades that lead to the advancement of atheroma.

Biogenic nanoparticles offer multiple strategies

Environmental remediation: pieces of polymers degrading in soil and water by adsorption or photocatalysis.
Biomedical intervention: Selectively binding microplastics with ligand-functionalized nanoparticles for therapeutic clearance or diagnostic imaging [40].
Understanding the biodistribution, clearance kinetics, and systemic safety of such therapies still presents difficulties.

Future Perspectives

The following are necessary for the advancement of biogenic nanoparticle technology: Accurate synthesis control through genetic and metabolic engineering.
In-depth ecotoxicology and biocompatibility profiling.
Multidisciplinary cooperation to create safety and regulatory frameworks. Biogenic nanoparticles are positioned as a technical cornerstone for sustainability and public health due to their incorporation into diverse methods against microplastic health risks, antibiotic resistance, and agricultural inefficiency.

Summary

Produced by the biological activity of microorganisms and substances produced from plants, biogenic nanoparticles are becoming more and more well-known as sustainable and adaptable agents with a wide range of uses in the environmental, medical, and agricultural fields [44]. Compared to their conventionally synthesized counterparts, these biologically mediated nanoparticles exhibit improved stability, functionalized surfaces, and greater biocompatibility. They are manufactured under mild, environmentally benign circumstances. They function as effective nano-fertilizers, nanoherbicides, and nanofungicides in agricultural systems, promoting better nutrient uptake, promoting plant development, and offering focused pest and phytopathogen management [47]. By lowering reliance on conventional chemical inputs and avoiding environmental contamination, this multifunctionality promotes sustainable farming [48].
Within the field of microbial management, biogenic nanoparticles demonstrate strong antibacterial capabilities that effectively break biofilms, which are intricate microbial consortia that are resistant to conventional therapies [49]. These nanoparticles provide promising methods for infection control, industrial biofouling prevention, and water quality preservation by interfering with microbial quorum sensing, breaking down biofilm extracellular polymeric substances, and producing reactive oxygen species to destroy these robust microbial structures.
Concurrently, recent studies highlight the harmful health effects of ubiquitous microplastics, which have been linked to the emergence of cardiovascular and atheroma disorders [52]. By adsorbing, breaking down, or neutralizing microplastic pollutants, biogenic nanoparticles have the potential to play crucial roles in this situation and lessen their toxicological consequences [53]. These multipurpose nanoparticles may also be used as platforms for treatment and diagnosis of vascular diseases brought on by microplastics [54].
It is still difficult to completely understand the toxicity profiles, environmental persistence, and regulatory compliance of nanoparticles, despite their enormous promise. Thorough research into these problems' long-term safety, environmental destiny, and mechanistic interactions is necessary to address them. At the end of the day, biogenic nanoparticles are revolutionary tools that can help reduce new health hazards associated with microplastics, fight illnesses linked to biofilms, and advance global food security initiatives [s]. They have great potential to address urgent issues in a variety of industries when incorporated into creative and sustainable technology frameworks.

Conclusion

Biogenic nanoparticles are a prime example of the fusion of biological creativity and nanotechnological accuracy, offering adaptable answers to worldwide problems in environmental health, infection prevention, and agriculture. Their biomedical value is expanded by their role in reducing vascular diseases caused by microplastics. However, systematized safety evaluations, standardization, and policy alignment are necessary for successful translation into broad practice. These nanomaterials may play a key role in advancing the next wave of integrative approaches to ecological resilience, healthcare, and food security as research into them continues.

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