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(Review Article)

Microbial routes to nanotechnology: Green synthesis, biofilm inhibition, agricultural applications and emerging links to microplastics in Atheromas

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Abstract

An emerging area of nanotechnology is the microbial synthesis of nanoparticles, which provides environmentally acceptable and sustainable substitutes for traditional physical and chemical manufacturing techniques. As natural nano factories, microorganisms like bacteria, fungus, actinomycetes, and microalgae mediate the reduction and stabilization of metal ions into nanoparticles with distinct physicochemical characteristics. These biogenic nanoparticles have great promise for use in a variety of industries, such as biofilm management, sustainable agriculture, and biomedical applications. They serve as nano-fertilizers, nano herbicides, and nano fungicides in agriculture, improving crop output, nutrient availability, and disease resistance while lessening their negative effects on the environment. They are useful instruments in the fight against persistent microbial communities in industrial, medicinal, and environmental settings because of their strong antibacterial qualities and capacity to break down biofilms. New research also shows how microplastics and nanoparticles interact in vascular settings, which may help explain how atheroma develops and how cardiovascular health is affected. The synthesis processes, structural and functional diversity, and uses of microbial nanoparticles in many industries are examined in this review. In addition, it examines how nanotechnology might be used to mitigate the health hazards associated with microplastics while assessing issues with toxicity, environmental destiny, and regulatory mechanisms. A strong, long-lasting framework for tackling urgent issues in environmental health, healthcare, and agriculture is provided by microbial nanotechnology taken together.

Keywords: Microbial Nanotechnology; Green Synthesis; Biofilm Inhibition; Sustainable Agriculture; Microplastics and Atheroma's

1. Introduction

Modern science and technology have been completely transformed by nanotechnology, which is the study of creating, engineering, and using materials at the nanometer scale (1–100 nm) [1,2]. Its exceptional capacity to take use of nanoscale phenomena—such as increased surface reactivity, adjustable physicochemical characteristics, and quantum effects—has resulted in revolutionary breakthroughs in a variety of industries, including environmental remediation, materials research, medicine, and agriculture [3]. Microbial techniques have become a viable, economical, and environmentally safe substitute for traditional physical and chemical methods in the synthesis of nanoparticles [4]. Because of their inherent biochemical properties, microorganisms such as bacteria, fungus, actinomycetes, and microalgae can stabilize nanoparticles and decrease metal ions through metabolite interactions and enzymatic reactions [5]. In addition to removing the need for hazardous chemicals and large energy inputs, this "green synthesis" produces nanoparticles capped with compounds derived from biology, improving their stability and biocompatibility [6,7].

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Numerous uses have been made possible by the special qualities of biogenic nanoparticles. Sustainable agriculture tackles pressing worldwide issues like environmental degradation and food security [8]. Microbially produced nanoparticles can be used as nanocarriers for regulated agrochemical release, nano herbicides and nano fungicides to control weeds and plant diseases, and nano-fertilizers to improve nutrient delivery [9]. These applications support precision agriculture and sustainable development by increasing crop output, lowering chemical inputs, and minimizing ecological effect [10]. Furthermore, it has been demonstrated that microbial nanoparticles improve soil health and activate plant defense mechanisms, hence enhancing agricultural resilience [11].

The suppression and control of biofilms is a key application area [12]. Because of their increased resistance to antibiotics and disinfectants, biofilms—structured microbial consortia encased in a self-produced extracellular matrix—present significant issues in the fields of industry, healthcare, and water treatment [13]. Traditional methods of biofilm removal frequently fall short of penetrating these tough structures [14]. By producing reactive oxygen species, penetrating extracellular polymeric materials, blocking quorum sensing, and improving antibiotic administration, biogenic nanoparticles provide a versatile option that can break up biofilms [15]. These qualities make microbial nanoparticles attractive options for treating chronic illnesses, avoiding biofouling, and enhancing the hygienic conditions of water systems [16].

The use of nanotechnology to comprehend and possibly lessen the negative health impacts of microplastics, especially their function in the development of atheroma, a crucial phase in cardiovascular disease, is an exciting new field. Nowadays ubiquitous in the environment and human food chain, microplastics can build up in tissues and cause inflammatory reactions that are connected to atherosclerosis [17]. Within biological systems, nanoparticles may interact with microplastics to affect their toxicity, transport, and biological destiny [18]. Furthermore, tailored nanoparticles may be used as therapeutic or diagnostic instruments to identify, break down, or eliminate microplastics and the hazards they pose [19]. A fascinating new line of inquiry with important public health ramifications is the convergence of nanotechnology and microplastic toxicity [20].

The goal of this review is to present a thorough analysis of the mechanics, characterization, and multipurpose uses of microbial pathways to nanoparticle formation [21]. It addresses issues with safety, environmental impact, and regulation while delving deeper into their potential in biofilm control, microplastic-associated vascular diseases, and agriculture [22]. Microbial nanotechnology is a flexible and potent instrument that can be used to address some of the most important scientific and socioeconomic issues of our day by combining microbiology, nanoscience, and environmental health [23].

2. Mechanisms of Microbial Nanoparticle Synthesis

Through environmentally benign, economical, and scalable methods, microorganisms have become potent biological platforms for the creation of metallic and metal oxide nanoparticles [24]. Without the need for harsh chemical reagents or high-energy inputs, their distinct metabolic and enzymatic systems allow the reduction of metal precursors and the stabilization of nanoscale products [25]. Microalgae, fungus, bacteria, and actinomycetes have all shown impressive capacities to function as "nano factories," generating nanoparticles with regulated surface chemistry, size, and shape [26].

Intracellular and extracellular synthesis are the two main paths that the biosynthesis process usually takes. By passing through the microbial cell wall and interacting with proteins, enzymes, and metabolites, metal ions can be converted to elemental nanoparticles by the intracellular route. Before being extracted by cell lysis, these nanoparticles are nucleated and develop in the cytoplasmic or periplasmic area. On the other hand, extracellular synthesis happens when metal ions are reduced outside of the cell by secreted enzymes and metabolites, which results in the creation of nanoparticles in the surrounding medium. While intracellular synthesis frequently produces nanoparticles with better structural control, the extracellular technique enables simpler downstream processing and scalability [27,28].

By moving electrons from co-factors like NADH or NADPH to metal ions, microbial enzymes like reductases and dehydrogenases play a crucial part in reducing metal ions. Furthermore, the capping agents—proteins, polysaccharides, and other biomolecules—stabilize the nanoparticles and stop them from aggregating. The size, shape, and crystallinity of the nanoparticles—which can have spherical, cubic, triangular, or rod-like structures—are all influenced by the biochemical environment that the microbial system provides [29,30].

The creation of nanoparticles is further influenced by environmental variables as pH, temperature, metal ion concentration, and incubation duration. For instance, temperature affects the kinetics of nucleation and development, whereas alkaline pH frequently encourages quicker reduction and smaller particle sizes. To customize nanoparticle characteristics for particular uses, these factors can be changed. A promising avenue for precision nanomaterial design is the use of genetically modified microorganisms, which present more chances to improve production, regulate particle properties, and add new functions [31,32].

3. Applications in Sustainable Agriculture

In the face of issues like soil erosion, climate change, and new plant diseases, the agricultural sector is under increasing pressure to feed the world's rapidly expanding population in a sustainable manner. Microbially produced biogenic nanoparticles present a revolutionary way to modernize agriculture while reducing environmental effects. They can act as nano-fertilizers, nonherbicides, nano fungicides, and carriers for regulated agrochemical delivery thanks to their special physicochemical characteristics [33].

By enhancing bioavailability, lowering leaching losses, and enabling delayed and tailored nutrient release, nano-fertilizers increase the efficiency of nutrient usage. For instance, bacterial and fungal-produced zinc oxide and iron oxide nanoparticles can provide micronutrients more efficiently than traditional fertilizers, increasing plant growth and production. Similarly, nanoparticles can reduce the frequency and amount of fertilizer application by carefully encapsulating and delivering macronutrients like phosphate and nitrogen [34,35].

Pesticides and fungicides based on nanoparticles exhibit strong antimicrobial action against a variety of phytopathogens in crop protection. For example, Pseudomonas and Aspergillus species biosynthesize silver nanoparticles, which have potent antifungal action against Alternaria and Fusarium species. These materials' effectiveness is increased by their ability to pierce plant tissues and pathogen biofilms due to their nanoscale size. Additionally, the risk of overapplication and environmental pollution is decreased by their controlled release characteristics [36].

Additionally, biogenic nanoparticles provide weed control methods. By focusing on particular metabolic pathways in weeds, nonherbicides can lessen herbicide resistance and off-target effects. Furthermore, some nanoparticles' elicitor and antibacterial qualities might boost plant defense systems, increasing tolerance to abiotic stressors and infections. By affecting microbial community dynamics and nutrient cycling, nanoparticles enhance soil health in addition to direct agricultural treatments [37].

Notwithstanding their potential, possible ecotoxicological issues must be addressed before using nanoparticles in agriculture. Nanoparticles can affect nutrient dynamics, interact with soil bacteria, or build up in the food chain. Before they are widely commercialized, thorough research on their long-term behavior, fate, and effects is essential. Standardized characterization procedures and regulatory frameworks will be essential to guaranteeing adoption that is both secure and long-lasting [38].

4. Role in Biofilm Inhibition and Control

Microorganisms are shielded from environmental stress, antibiotics, and disinfectants by biofilms, which are organized microbial consortia embedded in an extracellular polymeric matrix. Their resilience presents serious problems for industrial, water treatment, and healthcare systems. Because of their inherent antibacterial qualities and physicochemical diversity, biogenic nanoparticles present intriguing approaches for biofilm prevention, disruption, and eradication [39].

Biofilms are inhibited by nanoparticles in a number of ways. One main mechanism is membrane rupture, in which negatively charged microbial membranes are electrostatically contacted by cationic or amphiphilic nanoparticles, increasing permeability, allowing internal contents to seep out, and ultimately causing cell death. Microbially produced silver and copper nanoparticles have shown potent membrane-disruptive effect against bacteria that form biofilms, including Pseudomonas aeruginosa and Staphylococcus aureus [40].

The production of reactive oxygen species is another significant process (ROS). Proteins, lipids, and nucleic acids within biofilms are harmed by ROS, which are produced by redox processes that nanoparticles can catalyze. In addition to killing implanted cells, this oxidative stress also causes the extracellular matrix to become unstable. Additionally, the cell-to-cell communication mechanism that controls the formation of biofilms, quorum sensing, may be disrupted by nanoparticles. Quorum sensing disruption inhibits the formation of biofilms and lowers the generation of virulence factors [41].

These materials' nanoscale size also enables them to pass through the biofilm matrix, which is one of the main obstacles that traditional antibacterial agents face. Once within, nanoparticles can improve antibiotic activity, transport therapeutic payloads, and collectively compromise the integrity of biofilms. For instance, it has been demonstrated that mixing biogenic nanoparticles with traditional antibiotics lowers minimum inhibitory concentrations and restores antibiotic efficacy against infections linked to resistant biofilms [42].

Nanoparticle coatings on surfaces can reduce biofouling in water systems, pipelines, and medical devices in industrial and environmental environments by preventing initial microbial attachment. One possible strategy for long-term biofilm control is the integration of biogenic nanoparticles into membranes, filters, and coatings [43].

5. Interactions with Microplastics and Atheroma Formation

Plastic particles smaller than 5 mm, or microplastics, have become a common environmental contaminant with serious health effects on people. Recent research has connected exposure to microplastics to cardiovascular disorders, such as atheroma formation—the accumulation of lipid-rich plaques in artery walls—systemic inflammation, and oxidative stress. Developing ways to reduce these dangers requires an understanding of the interactions between nanoparticles and microplastics [44].

There are various ways in which biogenic nanoparticles could affect the behavior of microplastics in biological and environmental systems. They can first function as sorbents, attaching themselves to the surfaces of microplastics and changing their mobility, bioavailability, and physicochemical characteristics. By containing toxic compounds, this interaction may lessen the toxicity of microplastics or, on the other hand, increase their absorption into biological tissues [45].

Second, nanoparticles might act as catalysts to break down microplastics. Under environmental conditions, some metallic nanoparticles, such titanium dioxide or iron oxide, can produce reactive oxygen species (ROS), which can cause polymer chains to oxidatively degrade. Therefore, microbial nanoparticle systems might be designed to speed up the breakdown of microplastics in biological or environmental settings [46].

From a biological standpoint, nanoparticles have the potential to be used as therapeutic and diagnostic instruments to treat vascular diseases linked to microplastics. Functionalized nanoparticles may be utilized to deliver anti-inflammatory or anti-atherogenic medicines to afflicted areas or to identify the buildup of microplastics in tissues. Additionally, investigating the cellular and molecular interactions between nanoparticles and microplastics may provide fresh perspectives on the processes that connect environmental contaminants to cardiovascular disease [47].

Nonetheless, the coexistence of microplastics and nanoparticles in the environment also prompts questions regarding their possible synergistic effects and combined toxicity. Their interactions could affect immunological responses, biodistribution, and long-term health consequences. Therefore, in order to guide safe and efficient usage, thorough toxicological evaluations and mechanistic research are required [48].

6. Future Perspectives

A quickly developing topic, microbial pathways to nanotechnology is well-positioned to tackle important issues in environmental sustainability, healthcare, and agriculture. However, a number of significant obstacles must be removed before these advancements may be used in the real world from laboratory study. Since variations in microbial strains, culture conditions, and precursor materials can have a substantial impact on nanoparticle properties, future research must concentrate on standardizing biosynthetic processes. The generation of nanoparticles may become more predictable and adjustable with developments in metabolic engineering and synthetic biology [49].

Crop management in agriculture could be completely transformed by incorporating nanoparticle technologies into precision farming platforms; nevertheless, this calls for thorough research on the long-term effects on soil health, interactions between nanoparticles and plants, and food safety. Similar to this, combining nanoparticles with new therapeutic drugs or traditional antimicrobials in biofilm management promises intriguing synergy; nevertheless, regulatory approval and clinical validation are still necessary procedures [50].

A new field with important biomedical ramifications is the nexus between nanotechnology and microplastic toxicity. Novel diagnostic and treatment approaches for cardiovascular and other chronic diseases may result from understanding how nanoparticles affect microplastic behavior and related disease pathways [51].

The future of this discipline will ultimately be determined by the intersection of environmental health, materials science, nanotechnology, and microbiology. To fully utilize microbial nanotechnology for planetary health, disease prevention, and sustainable development, cooperative, multidisciplinary research initiatives will be crucial [52].

Summary

Using bacteria, fungus, actinomycetes, and microalgae as biological nano factories, microbial nanotechnology offers a sustainable method of creating useful nanoparticles [53]. By stabilizing metal ions with bio-organic molecules and reducing them into nanoscale materials, these organisms produce nanoparticles with improved surface reactivity, stability, and biocompatibility. Microbial synthesis is scalable, economical, and environmentally benign in contrast to traditional chemical or physical techniques. As nano-fertilizers, nonherbicides, and nano fungicides, biogenic nanoparticles are being used more and more in agriculture to improve nutrient delivery, crop resilience, and disease management while reducing their negative effects on the environment. Since nanoparticles can break down microbial membranes, pierce extracellular polymeric materials, produce reactive oxygen species, and obstruct quorum sensing, their antibiofilm properties are equally important [54,55]. These processes offer practical methods for overcoming enduring biofilms in water treatment, industrial systems, and healthcare. Recent studies have also connected microplastics to cardiovascular diseases such atheroma development, where nanoparticles may be useful for therapeutic intervention, degradation, or detection. They may lessen vascular inflammation and the advancement of illness by adsorbing or catalytically breaking down microplastics. Although encouraging, issues with nanoparticle toxicity, biodistribution, environmental destiny, and regulatory monitoring still exist. All things considered, microbial nanotechnology provides an environmentally friendly, adaptable platform to promote biofilm management, agricultural sustainability, and new understandings of the health hazards linked to microplastics [56,57,58].

7. Conclusion

Microbial pathways to nanotechnology combine creativity and sustainability to produce nanoparticles that tackle important issues in environmental protection, healthcare, and agriculture. Their multifunctional usefulness is demonstrated by their capacity to improve nutrition efficiency, inhibit pathogens, and regulate biofilms; additionally, their newfound responsibilities in reducing microplastic-associated atheroma's pave the way for novel biological developments. However, obstacles pertaining to safety, environmental effect, reproducibility, and regulatory clarity must be overcome for translation to be practicable. To guarantee safe deployment, standardized synthesis procedures, thorough toxicological analyses, and life-cycle assessments are necessary. Nanoparticle yield, uniformity, and functionalization can be enhanced by technological advancements including regulated biosynthetic pathways and omics-driven strain engineering. At the same time, establishing efficient administration and encouraging responsible innovation will require interdisciplinary cooperation between microbiologists, nanotechnologists, toxicologists, and legislators. These pillars must line up for microbial nanotechnology to move from lab research to practical uses, offering quantifiable advantages in infection prevention, cardiovascular health, and food security while preserving ecological sustainability.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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