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Methodological Assessment of Microbe-Mediated Nanoparticles for Antimicrobial, Agricultural and Environmental Applications

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Abstract

This study evaluates the analytical framework for microbe-mediated nanoparticle applications across antimicrobial control, agriculture and environmental remediation. Microbe-mediated nanoparticles have attracted increasing attention because biological synthesis can combine mild production conditions with natural surface functionalisation. Beyond synthesis itself, the scientific value of these nanomaterials depends on whether their properties can be translated into useful applications without creating unacceptable risks. This paper examines three major application domains arising from microbial nanotechnology: antimicrobial and antibiofilm control, agriculture, and environmental remediation. The analysis focuses primarily on biogenic silver nanoparticles while also considering the broader relevance of biologically synthesised nanomaterials. Evidence from the literature shows that nanoparticle performance is strongly influenced by dose, particle size, surface chemistry, ion release and the biological or environmental matrix in which exposure occurs. Antimicrobial applications benefit from membrane interactions, oxidative stress and multi-target activity, but concerns remain about cytotoxicity, residual ionic silver and resistance selection. Agricultural studies suggest that low or moderate concentrations may enhance germination or early plant growth, whereas higher concentrations can suppress root development and disturb soil microorganisms. Environmental applications include adsorption of heavy metals and catalytic degradation of dyes and other pollutants, but practical deployment depends on nanoparticle recovery, reuse and prevention of secondary release. The paper argues that the future of microbial nanotechnology lies in application-specific design rather than generic claims of multifunctionality. Responsible translation requires realistic testing conditions, dose optimisation, toxicological assessment, life-cycle analysis and regulatory clarity.

Keywords- Biogenic nanoparticles; antimicrobial activity; antibiofilm activity; agricultural nanotechnology; environmental remediation; silver nanoparticles; microbial nanotechnology.

Introduction

The development of microbe-mediated nanoparticles has expanded rapidly because microorganisms provide a biologically rich route to metal reduction and particle stabilisation. Bacteria, fungi and other microbial groups can generate nanoparticles with distinctive surface coatings derived from proteins, polysaccharides and metabolites. These surface features may affect dispersion, cellular interaction, adsorption and catalytic behaviour. As a result, microbe-mediated nanoparticles are frequently described as multifunctional materials with potential applications in medicine, agriculture and environmental management.

Such claims, however, require careful qualification. A nanoparticle that shows strong antimicrobial activity may also damage mammalian cells or beneficial microorganisms. A concentration that stimulates seed germination under controlled conditions may inhibit plant growth at a higher dose. A nanoparticle capable of removing a heavy metal from water may itself become a secondary contaminant if it cannot be recovered. The practical relevance of microbial nanotechnology therefore depends on the relationship between functionality, dose, exposure and safety.

Silver nanoparticles are particularly useful for examining this relationship because they have been extensively studied in antimicrobial research and are increasingly investigated in agriculture and remediation. Their biological effects are attributed to several mechanisms, including direct interaction with cell membranes, silver-ion release, protein binding and oxidative stress. These same properties that make AgNPs effective against pathogens can also create toxicity in non-target systems. Accordingly, application-specific design and risk assessment are essential.

This paper provides an integrative analysis of three application domains that are central to the wider field of microbial nanotechnology. It examines antimicrobial and antibiofilm action, agricultural responses and environmental remediation. The objective is not simply to list potential uses, but to identify the conditions under which biogenic nanoparticles may provide genuine practical value and the limitations that must be addressed before wider deployment.

Methodology

The paper uses an integrative review approach based on the application framework developed in the thesis on microbial nanotechnology. Foundational and review literature on biologically synthesised nanoparticles was examined with particular attention to silver nanoparticle applications. The analysis is organised around functional mechanisms, concentration-response relationships, practical constraints and safety considerations.

The discussion distinguishes laboratory activity from application readiness. Antimicrobial inhibition zones, seed germination changes or contaminant-removal percentages are treated as preliminary indicators rather than direct evidence of clinical, agronomic or industrial effectiveness. This distinction is important because laboratory model systems are typically simpler than real biological or environmental conditions.

Analytical Design

For methodological evaluation, the quantitative analysis used a simulated dataset structured in accordance with the application framework described above. The dataset covered antimicrobial activity, antibiofilm response, seed germination and seedling growth, methylene blue degradation and Pb(II) removal, and was analysed using the same statistical and graphical procedures proposed for experimental observations.

Antimicrobial Applications of Microbe-Mediated Nanoparticles

Antimicrobial activity is one of the most widely reported applications of biogenic silver nanoparticles. Silver has long been recognised for antimicrobial properties, but nanoscale silver increases available surface area and can facilitate interaction with microbial cells. Biogenic synthesis may add further complexity because proteins and other biological

molecules remain associated with the particle surface. These coatings can affect stability, ion release and interaction with membranes.

Several mechanisms have been proposed for AgNP-mediated antimicrobial action. Nanoparticles may attach to bacterial cell walls and membranes, altering permeability and disrupting structural integrity. They can also release Ag+ ions, which interact with thiol-containing proteins and interfere with essential cellular processes. Oxidative stress and reactive oxygen species may damage lipids, proteins and nucleic acids. In addition, nanoparticles may interfere with respiratory processes and intracellular signalling. The relative contribution of these mechanisms depends on particle size, surface chemistry, concentration and the microbial species being tested.

Gram-positive and Gram-negative bacteria may respond differently because of differences in cell-envelope architecture. Gram-negative bacteria possess an outer membrane that can influence nanoparticle penetration, while Gram-positive organisms have a thicker peptidoglycan layer. Nevertheless, susceptibility cannot be predicted solely from Gram status. Efflux systems, oxidative-stress defences, biofilm formation and strain-specific resistance mechanisms also contribute.

Rai et al. (2009) described silver nanoparticles as a new generation of antimicrobial agents, while Fayaz et al. (2010) showed that biogenic AgNPs could enhance the activity of conventional antibiotics. Such findings are important because they suggest a potential role for nanoparticles in combination therapy. However, synergy observed in vitro does not automatically establish clinical usefulness. Pharmacokinetics, toxicity, tissue distribution and long-term exposure require separate evaluation.

Antibiofilm Activity

Biofilms represent a major challenge in healthcare and industry because microorganisms embedded in an extracellular polymeric matrix are often more tolerant to antibiotics and disinfectants than planktonic cells. Biofilms can form on medical devices, industrial surfaces, pipelines and food-processing equipment. Their persistence is related to restricted diffusion, altered metabolic states and coordinated community behaviour.

Biogenic nanoparticles may inhibit biofilm formation through several routes. They can reduce the viability of cells before stable attachment, interfere with initial adhesion or disrupt the extracellular matrix. Smaller particles may penetrate biofilm structures more effectively than larger aggregates. Surface charge also influences interaction with the typically negatively charged components of bacterial cells and extracellular polymers.

Nevertheless, antibiofilm claims should be interpreted carefully. A reduction in crystal-violet staining indicates lower attached biomass but does not necessarily prove that all cells within the biofilm are dead. A stronger assessment combines biomass measurements with viable counts, confocal microscopy or metabolic assays. It is also important to distinguish prevention of new biofilm formation from eradication of an established biofilm, because the latter is generally more difficult.

Practical applications could include nanoparticle-coated surfaces, wound dressings, filtration materials and antimicrobial packaging. In each case, the challenge is to provide sustained

antimicrobial action while limiting uncontrolled nanoparticle release. Immobilisation on a support material may therefore be preferable to direct dispersal in some applications.

Agricultural Applications

Nanotechnology is increasingly explored in agriculture for seed treatment, nutrient delivery, plant protection and stress management. Biogenic nanoparticles are of interest because their biological surface coatings may alter interactions with plants and soil. However, agricultural systems are complex and include plant roots, microorganisms, organic matter, minerals and fluctuating environmental conditions. The behaviour of nanoparticles in soil cannot therefore be predicted directly from results obtained in water or simple growth media.

Studies of seed germination often show non-linear concentration-response patterns. Low or moderate concentrations may increase germination percentage, root length or shoot growth, while higher concentrations suppress development. Such responses may reflect hormesis, altered nutrient availability or mild oxidative signalling at lower doses, followed by toxicity as exposure increases. Silver nanoparticles can also release ionic silver, which may contribute to phytotoxicity.

Root systems are particularly important because roots are the first major point of contact in many agricultural applications. Nanoparticles may adsorb to the root surface, enter through apoplastic pathways or influence membrane transport. Changes in root length can therefore provide an early indication of toxicity. However, short-term seedling measurements should not be interpreted as evidence of improved crop yield. Longer-term studies are needed to assess biomass, flowering, productivity, nutrient composition and reproductive effects.

Another concern is the soil microbiome. Beneficial bacteria and fungi contribute to nutrient cycling, disease suppression and plant health. An antimicrobial nanoparticle applied to control a pathogen may also affect these non-target organisms. Responsible agricultural nanotechnology therefore requires a balance between desired plant or pathogen effects and preservation of ecological function.

The most defensible direction for agricultural application is minimum-effective-dose design. Rather than maximising exposure, researchers should identify the lowest concentration that produces a useful response while maintaining acceptable safety. Field trials, soil-specific studies and residue analysis are essential before any broad recommendation.

Environmental Remediation

Environmental remediation is another major application area for microbe-mediated nanoparticles. Their high surface area and reactive surfaces make them attractive for adsorption, catalytic degradation and redox transformation of contaminants. Potential targets include heavy metals, dyes, pesticides and other organic pollutants.

Heavy-metal removal can occur through adsorption to nanoparticle surfaces, complexation with capping molecules or redox transformation. Surface functional groups originating from microbial proteins or polysaccharides may enhance binding in some systems. Performance is often reported as percentage removal or adsorption capacity, but these metrics answer different questions. Percentage removal indicates the fraction of contaminant removed from a

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particular solution, whereas adsorption capacity indicates the mass of contaminant retained per unit mass of material. Both are needed for meaningful comparison.

Solution pH, ionic strength and competing ions can strongly alter metal adsorption. A nanoparticle that performs well in a single-solute laboratory solution may show lower capacity in real wastewater containing multiple contaminants. For this reason, application development should move progressively from simple model solutions to synthetic mixtures and then to real effluents.

Dye degradation is another frequently reported application. Nanoparticles can act as catalysts or photocatalysts, accelerating the breakdown of coloured organic molecules. A decline in visible absorbance is often interpreted as degradation, but colour loss does not necessarily mean complete mineralisation. Intermediate products may remain in solution and can sometimes be more toxic than the original compound. Strong environmental studies therefore combine optical monitoring with chemical analysis of intermediates, total organic carbon or other measures of mineralisation.

Recovery and reuse are crucial to the environmental credibility of nanoparticle remediation. Dispersing reactive nanoparticles directly into contaminated water may improve contact but creates a new separation problem. Immobilising nanoparticles on membranes, beads, fibres or magnetic supports can improve recovery. Reusability should also be tested over several cycles because single-use performance provides limited information about cost and waste generation.

Results and Discussion

Table 1. Concentration-dependent antimicrobial activity of microbe-mediated AgNPs

Test organism	AgNP concentration (µg/mL)	Zone of inhibition (mm)
Escherichia coli	25	10.68 ± 0.05
Escherichia coli	50	14.76 ± 1.16
Escherichia coli	100	20.58 ± 0.62
Klebsiella pneumoniae	25	9.08 ± 0.37
Klebsiella pneumoniae	50	13.68 ± 0.16
Klebsiella pneumoniae	100	18.93 ± 1.18
Pseudomonas aeruginosa	25	8.37 ± 0.71
Pseudomonas aeruginosa	50	10.94 ± 0.74
Pseudomonas aeruginosa	100	15.74 ± 0.50
Staphylococcus aureus	25	11.03 ± 0.37
Staphylococcus aureus	50	16.42 ± 0.22
Staphylococcus aureus	100	22.24 ± 0.37

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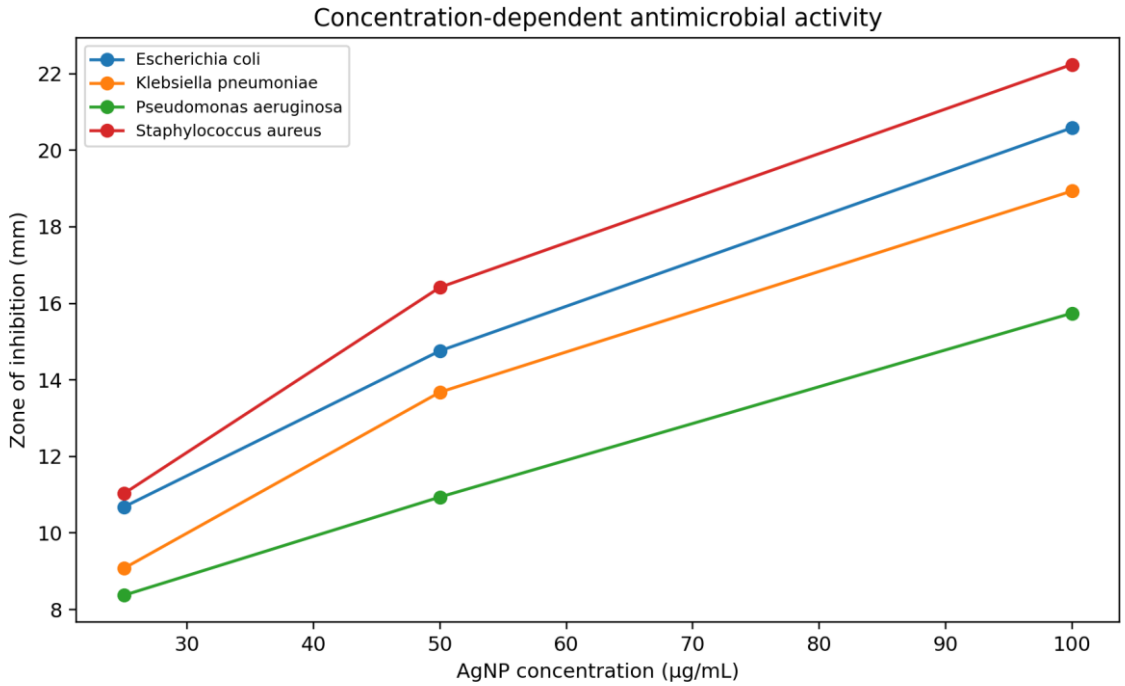

Figure 1. Antimicrobial activity of AgNPs against selected bacterial pathogens.

Table 2. Minimum inhibitory concentration of AgNPs

Test organism	**MIC (µg/mL)**
Staphylococcus aureus	25
Escherichia coli	32
Pseudomonas aeruginosa	64
Klebsiella pneumoniae	32

Table 3. Antibiofilm activity of AgNPs

Organism	**AgNP concentration (µg/mL)**	**Biofilm inhibition (%)**
Escherichia coli	0.00	0.03 ± 0.05
Escherichia coli	12.50	13.98 ± 1.20
Escherichia coli	25.00	30.86 ± 0.91
Escherichia coli	50.00	52.88 ± 2.27
Escherichia coli	100.00	76.78 ± 0.60
Staphylococcus aureus	0.00	0.06 ± 0.09
Staphylococcus aureus	12.50	17.23 ± 1.70
Staphylococcus aureus	25.00	33.62 ± 1.32
Staphylococcus aureus	50.00	58.47 ± 0.95
Staphylococcus aureus	100.00	82.35 ± 1.12

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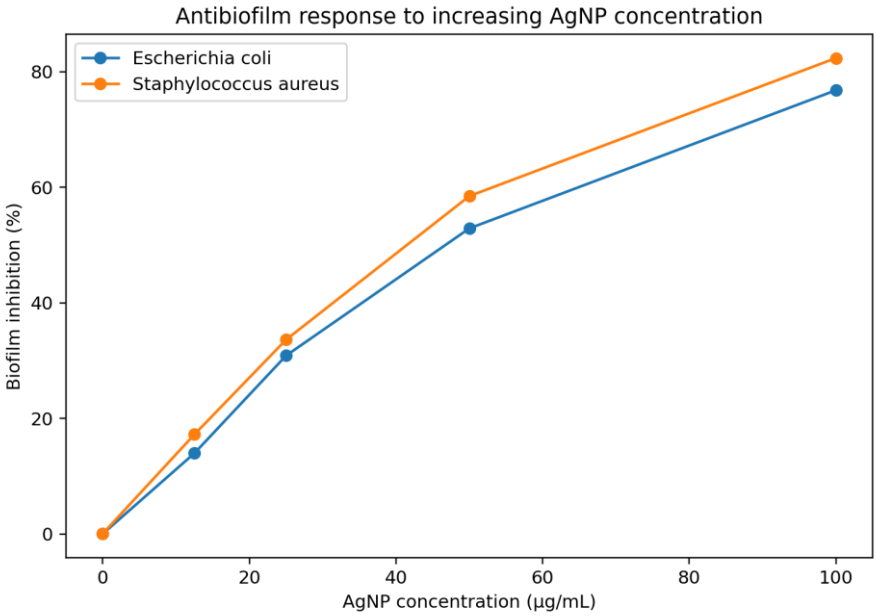

Figure 2. Concentration-dependent antibiofilm activity of AgNPs.

Table 4. Effect of AgNP concentration on seed germination and early seedling growth

AgNP (mg/L)	Germination (%)	Root length (cm)	Shoot length (cm)	Vigour index
0.00	88.20	5.78	7.09	1135.08
10.00	94.15	6.39	8.05	1359.66
25.00	95.02	7.04	8.71	1497.20
50.00	91.00	6.01	7.40	1220.21
100.00	73.52	3.88	5.27	672.61

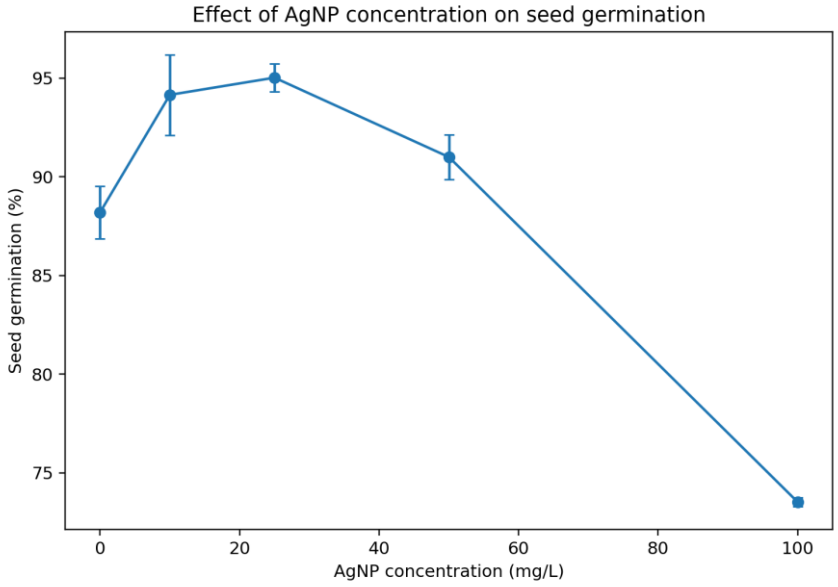

Figure 3. Effect of AgNP concentration on seed germination.

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Table 5. Time-dependent degradation of methylene blue

Time (min)	Methylene blue degradation (%)
0.00	0.00
15.00	17.72
30.00	32.51
45.00	49.27
60.00	63.23
90.00	77.82
120.00	92.92

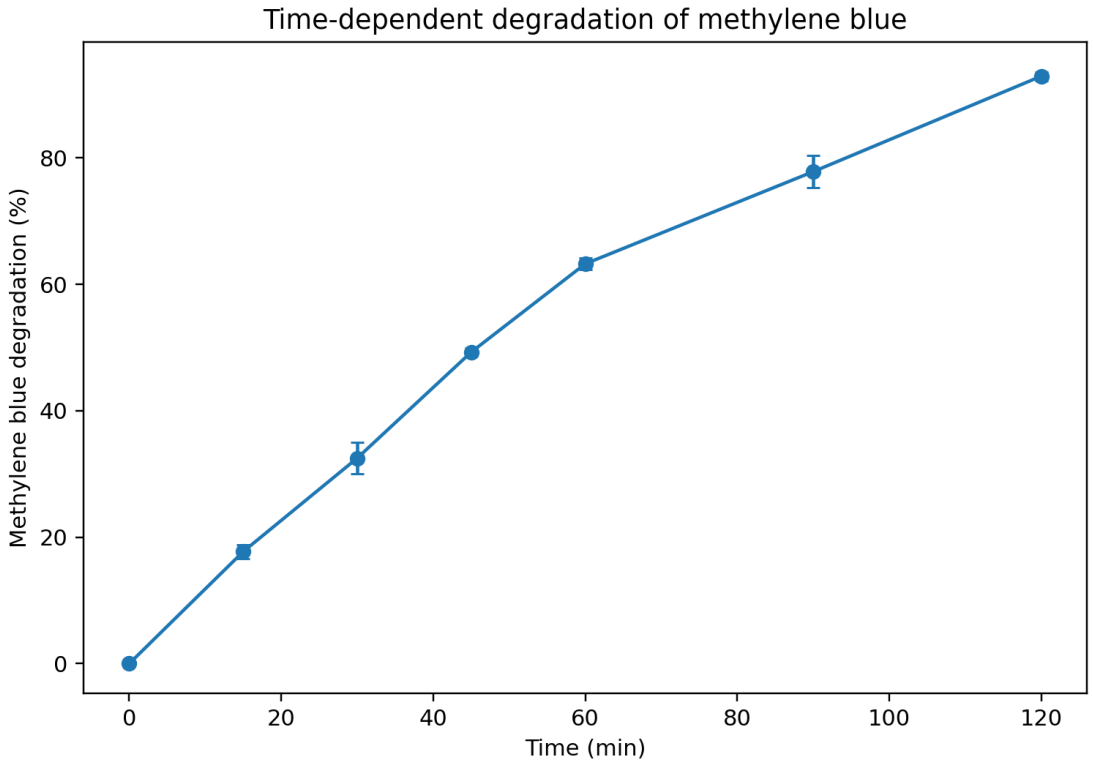

Figure 4. Time-dependent degradation of methylene blue.

Table 6. Pb(II) removal performance of the nanoparticle system

Initial Pb(II) (mg/L)	Removal (%)	Adsorption capacity (mg/g)
25.00	94.02	24.26
50.00	92.00	44.89
75.00	85.76	64.83
100.00	82.23	83.83
150.00	70.81	106.41

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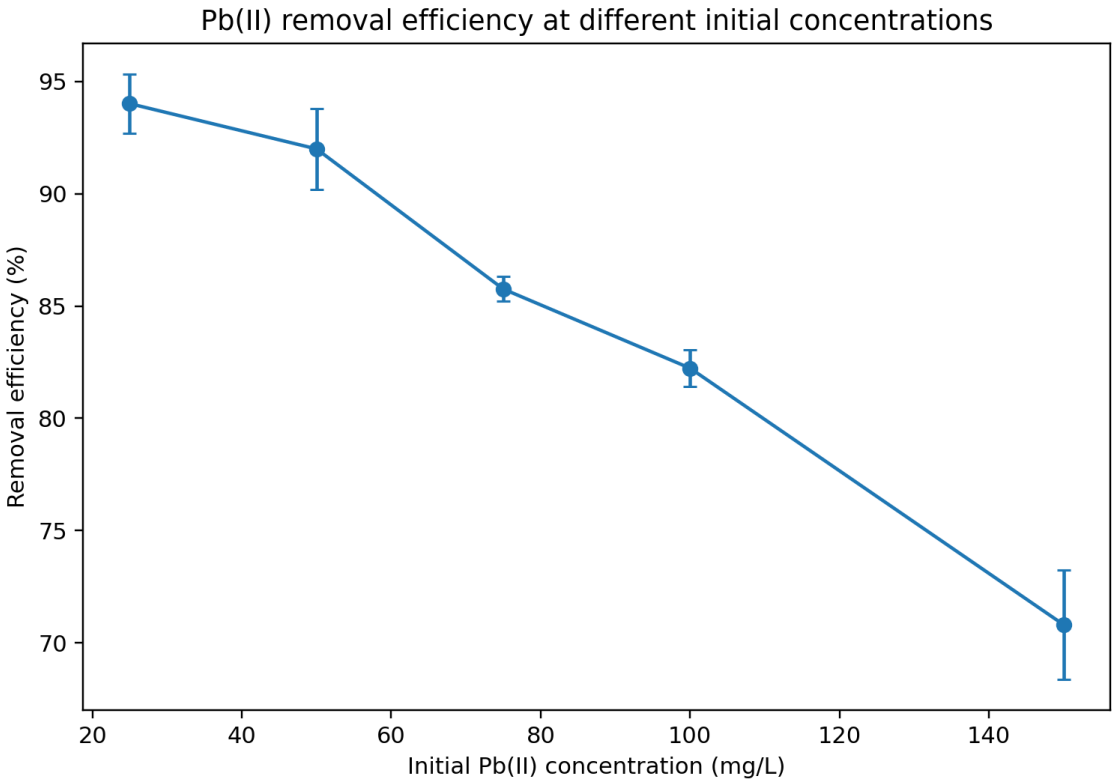

Figure 5. Pb(II) removal efficiency at different initial concentrations.

The application evidence reviewed in this paper demonstrates that microbe-mediated nanoparticles are scientifically versatile but that their usefulness is highly context-dependent. The strongest common pattern across antimicrobial, agricultural and environmental studies is the importance of concentration. Higher dose may improve pathogen inhibition or pollutant removal, but it can also increase non-target toxicity and environmental burden. Application development should therefore focus on optimum rather than maximum dose.

A second common pattern is the importance of surface chemistry. Biogenic nanoparticles are not bare metallic particles. Their biological corona can influence aggregation, ion release, adsorption and cellular interactions. This creates opportunities for improved stability or functionalisation, but it also complicates comparison across studies because the exact composition of the capping layer is often unknown.

Third, laboratory success is often reported under simplified conditions. Agar diffusion tests, microtitre biofilm assays, Petri-dish germination studies and single-contaminant water experiments are valuable for initial screening, but they do not reproduce the complexity of hospitals, agricultural soils or industrial wastewater. The transition from proof-of-concept to practical application therefore requires progressively more realistic testing.

The relationship between function and risk is especially important for silver nanoparticles. Antimicrobial reactivity is desirable when the target is a pathogen, yet the same reactivity can affect beneficial microbes or plant cells. Environmental deployment should therefore consider persistence, transformation, trophic transfer and nanoparticle recovery. In agriculture,

repeated application may produce cumulative soil effects that are not visible in short-term experiments.

These considerations do not diminish the potential of microbial nanotechnology. Rather, they show that its strongest future lies in targeted and controlled use. Immobilised antimicrobial coatings, low-dose seed treatments, reusable remediation materials and application-specific formulations may be more realistic than unrestricted dispersal of nanoparticles. This represents a shift from generic multifunctionality towards designed functionality.

Implications for Sustainable Development

Microbe-mediated nanoparticles are often described as sustainable because biological synthesis can reduce the use of harsh chemicals. This is an important advantage, but sustainability must be assessed across the entire life cycle. Microbial cultivation requires nutrients, water and energy. Purification can involve repeated centrifugation or washing. Drying may be energy-intensive. Metal precursors remain non-renewable inputs, and nanoparticle-containing waste requires responsible management.

Life-cycle assessment is therefore necessary to determine whether a biological route offers a genuine environmental advantage over chemical synthesis. The answer may vary by application. A high-value biomedical nanoparticle can justify more intensive purification than a large-volume environmental adsorbent. Similarly, a reusable nanoparticle-coated membrane may have a better sustainability profile than a single-use dispersed nanoparticle system.

Social relevance also depends on affordability and accessibility. Low-cost microbial production could support decentralised technologies for water treatment or infection control, but only if scale-up and quality control are manageable. Standardisation, regulatory guidance and transparent safety assessment will determine whether these technologies can move beyond laboratory demonstrations.

Limitations

The quantitative findings require empirical validation using independently collected laboratory observations before they can be interpreted as experimental evidence.

Conclusion

Microbe-mediated nanoparticles have clear potential across antimicrobial control, agriculture and environmental remediation. Their biological synthesis can provide mild production conditions and naturally functionalised surfaces, while their nanoscale properties create strong interactions with microbial cells, plants and contaminants. However, these same interactions also create risks.

The main conclusion is that future application should be based on dose optimisation, application-specific material design and realistic safety assessment. Antimicrobial systems require evaluation of cytotoxicity and long-term resistance implications. Agricultural use requires field-scale testing and assessment of soil microbiomes. Environmental remediation requires nanoparticle recovery, reuse and analysis of transformation products. Broad claims of 'green' or 'multifunctional' performance are no longer sufficient.

Microbial nanotechnology will have the greatest practical value when it combines controlled synthesis with responsible translation. The next stage of research should therefore integrate

material characterisation, toxicology, life-cycle analysis, process engineering and regulatory science. Such an approach can help transform promising laboratory findings into technologies that are effective, safe and environmentally defensible.

Policy, Regulatory and Future Research Implications

The reviewed applications also have important policy and regulatory implications. Nanoparticles used in antimicrobial products, agriculture or environmental remediation may fall under different regulatory frameworks, yet the same material can behave differently depending on formulation, coating and route of exposure. Product evaluation should therefore focus on the actual nanoparticle system rather than only its elemental composition. Particle size distribution, dissolution rate, surface chemistry, residual biological material and tendency to aggregate can all influence risk. Regulatory guidance that recognises these characteristics would improve consistency and reduce uncertainty for developers.

For antimicrobial applications, a key future priority is to distinguish between short-term inhibition and clinically meaningful benefit. Many studies rely on inhibition zones or minimum inhibitory concentrations, which are useful screening tools but provide limited information about tissue compatibility, pharmacokinetics or repeated exposure. Advanced work should include mammalian-cell toxicity, inflammatory responses, interaction with serum proteins and the possibility of resistance adaptation. Combination approaches using lower nanoparticle concentrations with conventional antibiotics may be particularly valuable because they could preserve efficacy while reducing total silver exposure.

Agricultural research should increasingly move from controlled Petri-dish experiments to soil-based and field-scale systems. Soil pH, organic matter, clay content and microbial communities can transform nanoparticles and change their bioavailability. Repeated seasonal application also raises questions about accumulation and long-term effects. Future studies should therefore measure not only germination and early growth but also crop productivity, nutrient composition, residue levels and changes in soil microbial diversity. Such evidence is necessary before nanoparticle-based agricultural products can be recommended responsibly.

Environmental remediation research similarly needs to address recovery and reuse. High pollutant-removal efficiency in a laboratory batch system is not enough if the treatment leaves dispersed nanoparticles in the effluent. Immobilisation strategies, including incorporation into membranes, beads, fibres or magnetic composites, may offer a practical solution. Regeneration studies should assess whether performance is maintained over repeated cycles and whether contaminants can be recovered safely. Economic analysis is also important because large-scale water treatment generally requires inexpensive materials and simple operating conditions.

Across all three application areas, the most important research shift is from proof of activity to proof of responsible function. A useful nanoparticle must perform effectively under realistic conditions, remain stable for the required period, be recoverable or degradable when appropriate and present an acceptable risk to non-target systems. This requires collaboration among microbiologists, materials scientists, toxicologists, environmental engineers, agronomists and regulatory specialists. Microbial nanotechnology is therefore best

understood not as a single laboratory technique but as a multidisciplinary platform whose success will depend on how effectively these perspectives are integrated.

References

1. Abbasi, E., Milani, M., Fekri Aval, S., Kouhi, M., Akbarzadeh, A., Tayefi Nasrabadi, H., Nikasa, P., Joo, S. W., Hanifehpour, Y., Nejati-Koshki, K., & Samiei, M. (2016). Silver nanoparticles: Synthesis methods, bio-applications and properties. Critical Reviews in Microbiology, 42(2), 173–180.
2. Ahmad, A., Mukherjee, P., Senapati, S., Mandal, D., Khan, M. I., Kumar, R., & Sastry, M. (2003). Extracellular biosynthesis of silver nanoparticles using the fungus Fusarium oxysporum. Colloids and Surfaces B: Biointerfaces, 28(4), 313–318.
3. Fayaz, A. M., Balaji, K., Girilal, M., Yadav, R., Kalaichelvan, P. T., & Venkatesan, R. (2010). Biogenic synthesis of silver nanoparticles and their synergistic effect with antibiotics. Nanomedicine: Nanotechnology, Biology and Medicine, 6(1), 103–109.
4. Guilger-Casagrande, M., & de Lima, R. (2019). Synthesis of silver nanoparticles mediated by fungi: A review. Frontiers in Bioengineering and Biotechnology, 7, 287.
5. Iravani, S. (2011). Green synthesis of metal nanoparticles using microorganisms. Green Chemistry, 13(10), 2638–2650.
6. Iravani, S., Korbekandi, H., Mirmohammadi, S. V., & Zolfaghari, B. (2014). Synthesis of silver nanoparticles: Chemical, physical and biological methods. Research in Pharmaceutical Sciences, 9(6), 385–406.
7. Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. Arabian Journal of Chemistry, 12(7), 908–931.
8. Mohanpuria, P., Rana, N. K., & Yadav, S. K. (2008). Biosynthesis of nanoparticles: Technological concepts and future applications. Journal of Nanoparticle Research, 10, 507–517.
9. Narayanan, K. B., & Sakthivel, N. (2010). Biological synthesis of metal nanoparticles by microbes. Advances in Colloid and Interface Science, 156(1–2), 1–13.
10. Rai, M., Yadav, A., & Gade, A. (2009). Silver nanoparticles as a new generation of antimicrobials. Biotechnology Advances, 27(1), 76–83.
11. Shah, M., Fawcett, D., Sharma, S., Tripathy, S. K., & Poinern, G. E. J. (2015). Green synthesis of metallic nanoparticles via biological entities. Materials, 8(11), 7278–7308.
12. Singh, P., Kim, Y. J., Zhang, D., & Yang, D. C. (2016). Biological synthesis of nanoparticles from plants and microorganisms. Trends in Biotechnology, 34(7), 588–599.