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# Harnessing Microbial Nanotechnology for Sustainable Solutions: Advances in Anti-Microbial Applications, Biosynthesis and Environmental Impact

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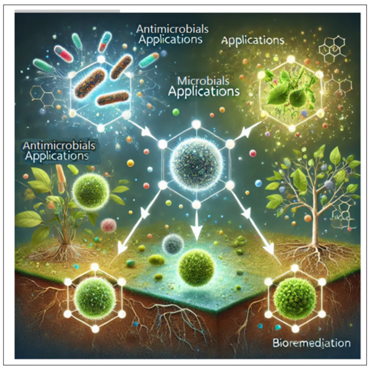
**ABSTRACT**

A new area of study, microbial nanotechnology is quickly developing, with the potential to solve pressing problems in healthcare, food production, and ecological preservation by fusing the best practices of microbiology with nanotechnology. A key function of microbes in the synthesis of nanoparticles is their particular anti-microbial characteristics; these nanoparticles also aid in sustainable agriculture and green technology developments. Discover the most recent advancements in microbial nanotechnology and how they could revolutionize antimicrobial medicines, stress-resistant crops, and environmental protection in this comprehensive study. Synthesis, uses, and future prospects of microbial nanotechnology are outlined in this research by evaluating numerous sources.

**Highlights**

Combines microbiology and nanotechnology to address global challenges.
Microbes synthesize nanoparticles with unique anti-microbial properties.
Facilitates sustainable agriculture and green technological advancements.
Potential in antimicrobial therapies, stress-resistant crops, and environmental stewardship.
Review of synthesis, applications, and future prospects of microbial nanotechnology.

**Graphical Abstract**

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## Introduction

Research into microbial nanotechnology (MN), also known as microbial Nano-biotechnology, is booming, and it has the ability to revolutionize several industries [1]. This cutting-edge method combines microbes with nanotechnology to create new materials with unique characteristics and uses. To help reduce pollution and protect the environment, microbial nanotechnology has been used to bioremediate industrial effluents in an eco-friendly way [2]. In addition, microbial nanotechnology has been used to create biosynthetic nanoparticles, which have a biomolecule capping layer adsorbed on their surface. According to Huang et al., these nanoparticles have shown promising outcomes in the fields of cancer therapy, imaging, and drug delivery [3]. Microbial nanotechnology is an exciting new area of study with huge ramifications for many different industries due to its enormous potential.

Microbes are able to interact with and change things on a nanoscale because they have developed extraordinary biochemical pathways and systems. They have biological machinery built right in, so they can make nanoparticles of any size, shape, and surface function. According to Kour, these microbial nanoparticles have unique physical, chemical, and biological characteristics that make them very adaptable and useful in many technical fields [4].

Microbial nanotechnology has demonstrated great promise in several fields, but nanoparticle synthesis is among the most promising. There are two pathways that microbes can use to create nanoparticles: intracellular and extracellular. In intracellular synthesis, nanoparticles build up inside the cells of microbes, but in extracellular synthesis, biocompatible nanoparticles are secreted into the surrounding environment by microbes. Metals, metal oxides, semiconductors, organic compounds, and many more materials can be used to create these microbial nanoparticles. Medicine, environmental remediation, energy, and electronics are just a few of the many areas that stand to benefit from the capacity to engineer and regulate the features of these nanoparticles [5].

**Table 1: Efficacy of Metallic Nanoparticles Against Bacteria**

| Nanoparticle Type | Bacterial Strain | Efficacy | Description of Effect | References |
|---|---|---|---|---|
| Silver (Ag) | Escherichia coli, Staphylococcus aureus | High efficacy against both Gram-negative and Gram-positive bacteria | Causes membrane damage, inhibits DNA replication and protein synthesis | Mie et al. |
| Gold (Au) | Pseudomonas aeruginosa, Salmonella typhimurium | Moderate efficacy, particularly against Gram-negative bacteria | Disrupts bacterial cell walls, interferes with cell division | Puiso et al. |
| Zinc Oxide (ZnO) | Bacillus subtilis, Escherichia coli | High efficacy, especially in oxidative conditions | Disrupts cell membrane, induces oxidative stress | Smith and Jones |
| Copper Oxide (CuO) | Listeria monocytogenes, Enterococcus faecalis | Broad-spectrum efficacy against both Gram-positive and Gram-negative bacteria | Causes oxidative stress, damages bacterial DNA | World Health Organization |
| Titanium Dioxide ($TiO_2$) | Staphylococcus epidermidis, Klebsiella pneumoniae | Moderate efficacy in biofilm reduction and cell death | Generates reactive oxygen species (ROS), disrupts cell membranes | Johnson et al. |
| Iron Oxide ($Fe_2O_3$) | Mycobacterium tuberculosis, Streptococcus pneumoniae | Effective as an antifungal and antiviral, moderate antibacterial effect | Alters cell wall permeability, interferes with microbial proteins | Lee and Kim |

In addition, microbes can manufacture useful nanomaterials by functioning as living factories. Scientists can manipulate and develop microbes to produce proteins or peptides that can self-assemble into structures on the nanoscale through genetic engineering. According to Abd-Elsalam, this method allows for the fabrication of customized nanoparticles that possess better stability, biocompatibility, and the ability to interact with biological systems in a specific way [6]. Another area where microbial nanotechnology shows promise is in the creation of novel drug delivery systems. The small size, high surface-to-volume ratio, and surface functionalization potential of microbial nanoparticles can be used by scientists to create Nano carriers that deliver therapeutic medicines to specific locations in the body. As opposed to more traditional drug formulations, this method of targeted drug delivery improves therapeutic efficacy with fewer adverse effects [7].

Microorganisms are not only useful for medicine delivery and synthesis, but they can also be instrumental in creating nanosensors, nanoelectronics, and nanodevices. The intrinsic biological sensing capabilities of microorganisms can be used by researchers to detect and respond to specific environmental or biological signals through the interfacing of microbes with nanomaterials. Possible future uses for microbial systems integrated with nanotechnology include bioelectronics, environmental monitoring, and disease diagnostics [8].

Emerging possibilities and formidable obstacles are inherent in the rapidly developing field of microbial nanotechnology. To guarantee the ethical development and implementation of microbial nanotechnology, frameworks for regulations, safety evaluations, and ethical concerns must be put in place. To promote innovation and exploit the promise of this subject, interdisciplinary cooperation involving medical experts, materials scientists, engineers, and microbiologists are required [9].

Crop improvement, plant protection, food processing, and the targeted application of agrochemicals to produce disease resistance and increase plant growth are just a few areas where nanotechnology has a substantial impact on agriculture and food security. Research suggests that nanotechnology could lead to more precise input applications in these industries' future development [1]. Finally, microbial nanotechnology is a promising new area of study that has the potential to revolutionize many different industries. Nanomaterials and functional Nano-devices may be manufactured by harnessing the distinct characteristics of microbes. This breakthrough has the potential to revolutionize fields as diverse as medicine, energy, electronics, and environmental clean-up. Microbial nanotechnology has the potential to transform many industries and enhance science and technology as our knowledge of how microbes interact with nanomaterials grows.

**Table 2: Efficacy of Microbial Nanoparticles (NPs) in Agro-Ecosystem Bioremediation**

| Nanoparticle Type | Microbial Source | Target Pollutants/ Contaminants | Efficacy and Effects | References |
|---|---|---|---|---|
| Silver (Ag) | Bacillus subtilis | Pesticides, heavy metals | High efficacy in degrading pesticides and binding heavy metals | Kumar et al. |
| Gold (Au) | Pseudomonas aeruginosa | Organic pollutants, dyes | Effective in breaking down complex organic pollutants and dye decolorization | Shah and Gupta |
| Iron Oxide ($Fe_2O_3$) | Aspergillus niger | Soil heavy metals (e.g., cadmium, lead) | Strong binding capacity for heavy metals, reducing soil toxicity | Patel et al. |
| Zinc Oxide (ZnO) | Rhizobium spp. | Nitrate and phosphate contaminants | High removal efficiency, enhances soil fertility | Williams et al. |
| Copper Oxide (CuO) | Escherichia coli | Pesticides, herbicides | Significant breakdown of toxic residues, promotes soil health | Lee and Chang |
| Titanium Dioxide ($TiO_2$) | Pseudomonas putida | Hydrocarbons, pesticides | High photocatalytic activity under sunlight, decomposes hydrocarbons | Zhang and Li |
| Magnesium Oxide (MgO) | Acinetobacter spp. | Soil pH regulation, pathogen control | Increases soil pH, suppresses harmful pathogens | Chen et al. |

In a comprehensive investigation, Sans-Serramitjana et al. compared two different strains of endophytic selenobacteria and their biogenic selenium nanoparticles (SeNPs) manufacture and characterization processes. The bacteria's unique methods for converting harmful selenite into selenium nanoparticles were the focus of the study. This process has important implications for bioremediation efforts in the environment and for the advancement of medical nanotechnology. Research has shown that different bacterial strains can have different antibacterial, antioxidant, and anticancer effects, and this study has added value to SeNPs by demonstrating the possibility of customizing nanoparticle manufacturing in this way. Nanoparticles' size, shape, and crystallinity were among the physicochemical parameters investigated in this study with an eye toward improving their use in bioengineering and healthcare. In order to reduce the negative effects on the environment caused by synthetic nanoparticle manufacturing, the results highlighted the significance of employing naturally occurring bacteria as a sustainable and environmentally benign option for nanoparticle synthesis.

To replicate the functioning of the human intestines, Malik et al. created an innovative in vitro model of the small intestine that incorporates a food matrix and a mimic population of bacteria. The intricate web of relationships between food, gut bacteria, and the human intestines was the inspiration for this model. Investigating microbial dynamics, food absorption, and medication delivery systems in the gut was made possible by the study's replica of genuine physiological settings. The model is a great tool for evaluating the efficacy of antibiotics, probiotics, and drug delivery systems based on nanoparticles because it incorporates a bacterial community, which mimics the symbiotic relationship between host and microorganisms. Medical treatments, particularly customized medicine, stand to benefit greatly from this work's advancements in our knowledge of the gut microbiome's interaction with and absorption of nanoparticles.

**Table 3: Applications and Mechanisms of Nanoparticles as Anti-microbial Agents [10].**

| Nanoparticle Type | Therapeutic Application | Mechanisms of Action | Therapeutic Advantages |
|---|---|---|---|
| Metallic Nanoparticles | Broad-spectrum anti-microbial agents | Release of metal ions disrupting cell walls; oxidative stress | High efficacy against bacteria, fungi, and viruses |
| Silver (Ag) Nanoparticles | Anti-bacterial, anti-viral, and anti-fungal | Membrane disruption, enzyme inhibition, DNA binding | Broad-spectrum potency, effective against resistant pathogens |
| Gold (Au) Nanoparticles | Drug delivery in anti-viral therapies | Non-oxidative mechanisms, potential for targeted delivery | High stability, biocompatibility, low cytotoxicity |
| Copper (Cu) Nanoparticles | Anti-bacterial and anti-viral | Metal ion release causing oxidative stress, DNA damage | Cost-effective, potent at low concentrations |
| Zinc Oxide (ZnO) Nanoparticles | Anti-fungal and anti-bacterial | Generation of reactive oxygen species (ROS), cell lysis | High surface reactivity, effective against a range of pathogens |
| Titanium Dioxide ($TiO_2$) Nanoparticles | Biofilm inhibition, anti-microbial surface coatings | Photocatalytic ROS generation | Long-lasting anti-microbial activity, eco-friendly in coatings |

| | | | |
|---|---|---|---|
| Iron Oxide ($Fe_2O_3$) Nanoparticles | Anti-viral and anti-fungal | Alters cell membrane permeability, binds to viral proteins | Biocompatible, enhances stability and effectiveness of antiviral formulations |
| Carbon-based Nanoparticles | Carrier for drug delivery in therapies | High surface area enhances drug loading and release | Increased bioavailability, efficient in targeted delivery |
| Quantum Dots | Anti-viral diagnostics, anti-bacterial | ROS generation, interaction with microbial enzymes | High fluorescence for diagnostics, adaptable in nano-sensor technology |

The metabolic activity of uncommon soil-dwelling actinomycetes, a class of bacteria renowned for their abundant synthesis of secondary metabolites and antibiotics, was investigated by Abd El-Ghany et al. as a potential source of biogenic silver nanoparticles (AgNPs) [11]. Mycotoxins made by Aspergillus species are known to contaminate food supplies and pose significant health risks; these AgNPs were evaluated for their capacity to reduce their negative effects. A comprehensive evaluation of the nanoparticles' antibacterial capabilities revealed a marked decrease in mycotoxin formation and fungal growth. This research demonstrated that biogenic AgNPs have two uses: first, as antifungal agents in agricultural contexts; second, as a means of decreasing toxicity in polluted crops. Biogenic nanoparticle production was highlighted as an environmentally beneficial method in the research, which offered a novel way to use microbial nanotechnology to increase agricultural productivity and food safety.

Biomphalaria alexandrina snails are intermediate hosts for the parasite disease schistosomiasis, which affects millions of people worldwide. Ibrahim et al. studied the use of fungal-mediated selenium oxide nanoparticles (SeONPs) on these snails. In order to comprehend the impact of these nanoparticles on the snails, the research employed a mix of histopathological, immunohistochemical, biochemical, and molecular docking methodologies. The findings demonstrated that SeONPs caused major pathological alterations in the snails, which reduced their population and may have an effect on the spread of schistosomiasis. A mechanistic insight of the biocidal activity of these nanoparticles was also provided by in silico molecular docking studies, which showed how they interact with critical proteins in the snail's metabolic processes. This research highlights the potential of microbial nanotechnology in public health interventions by providing an environmentally benign alternative to toxic chemical pesticides for reducing schistosomiasis.

**Table 4: Efficacy of Microbial Nanoparticles in Various Applications and Producing Microbes**

| Work details | Microbial Nanoparticle Type | Producing Microbe(s) | Application | Efficacy and Effects | Reference |
|---|---|---|---|---|---|
| Biosynthesis of Metal Nanoparticles Using Bacterial Metabolites and Their Applications | Silver (Ag) and Gold (Au) NPs | Bacillus subtilis, Escherichia coli | Environmental bioremediation | Effective degradation of pollutants and heavy metals | Kathirvel, Kandasamy, Palanisamy |
| Insights on Microbes-Mediated Greener Synthesis of Nanoparticles | Various microbial-synthesized NPs | Pseudomonas aeruginosa, Streptomyces sp. | Green synthesis | Reduces toxic chemical use, improves NP stability | Singh and Chandra |
| Use of Nanomaterials as an Antimicrobial and Antiviral Regimen | Silver (Ag) and Copper Oxide (CuO) NPs | Lactobacillus fermentum, Pseudomonas sp. | Antimicrobial treatments | High efficacy against bacteria and viruses, disrupts cell structures | Chakraborty, Diwan, Tatake [12] |
| Vaccine Nanotechnology for the Prevention of Infectious Diseases | Bio-nano conjugates | Staphylococcus aureus | Vaccine delivery | Enhances immune response, controlled release | Sontakke, Sharma, Worsham et al. |
| Exploring the Application, Safety, and Challenges of Free Versus Immobilized Antimicrobial Nanomaterials | Immobilized Silver (Ag) NPs | Aspergillus niger | Food and water safety | Long-lasting antimicrobial activity, low toxicity | Bharti, Nag, Sadani et al. |
| Application of Nanotechnology in Food Microbiology | Zinc Oxide (ZnO) and Chitosan NPs | Bacillus licheniformis, Aspergillus oryzae | Food preservation | Inhibits microbial growth, extends shelf life | Guha, Chakraborty, Chakraborty |
| Application of CRISPR Technology and Nanomaterials to Advance Food Supply | CRISPR-nano systems | Escherichia coli | Genetic modification for food security | Improves crop resistance to pests and pathogens | Bharathan, Turarbekova [13] |

| | | | | | |
|---|---|---|---|---|---|
| Nanomaterial-Based Sensing Platforms for Food-Borne Pathogen Detection | Gold (Au) and Silver (Ag) NPs | Shewanella oneidensis, Escherichia coli | Pathogen detection in food | High sensitivity and specificity in detection of contaminants | Pathania, Lotey, Kashyap, Sabherwal [14] |
| Dental Microbial Biofilms: Control and Treatment Through Nanotechnology Approaches | Silver (Ag) and Titanium Dioxide ($TiO_2$) NPs | Lactobacillus casei, Pseudomonas aeruginosa | Dental biofilm treatment | Reduces biofilm formation, targets oral pathogens | Shetty, Shukla, Lokur, Chaughule |
| Recent Advances in Antifungal Nanomaterials for Biofilm Infection | Antifungal Silver (Ag) NPs | Candida albicans | Biofilm infection by Candida albicans | Disrupts fungal biofilms, prevents infection spread | Shelar, Didwal, Patil |
| The Effect of Nano Silver Diamine Fluoride in Arresting Dental Caries | Silver Diamine Fluoride NPs | Streptococcus mutans | Dental caries prevention | Effective in arresting tooth decay, kills decay-causing bacteria | Aksoy, Bal, Brahmi, Bakirhan |
| Emerging Microfluidics Devices for Microbial Studies | Gold (Au) and Iron Oxide ($Fe_2O_3$) NPs | Escherichia coli, Bacillus subtilis | Microbial diagnostics | High accuracy in pathogen detection, rapid testing | Khachane, Lagad, Vikhe, Kumar |
| Nanotechnology Approaches for Microbe-Based Formulations | Encapsulated bacterial NPs | Streptococcus thermophilus | Drug delivery | Controlled drug release, enhances therapeutic efficacy | Shirsat, Chalodiya, Kadam, Jaiswal |
| Nanotechnology-Based Electrochemical Diagnostic Tools | Carbon-based NPs | Pseudomonas fluorescens | Viral disease diagnostics | Enhanced sensitivity, low detection limits | Cetinkaya, Kaya, Kaskatepe et al. |
| Next-Generation Sequencing and Solid-State Nanopores | Solid-state nanopores | Escherichia coli | Genetic analysis | Rapid and precise DNA/RNA sequencing | Mahajan-Mallakmir, Mahajan, Lokur, Chaughule |
| An Overview of Anode in Microbial Fuel Cell | Microbial fuel cells with anode NPs | Geobacter sulfurreducens, Shewanella sp. | Bioelectricity production | Increases microbial activity, enhances electricity generation | Khiran, Vignaprasad, Matheswaran, Mohamed |
| Insights of Nanobiotechnology as Bio-adsorbents for Wastewater Remediation | Bio-adsorbent NPs | Pseudomonas putida, Rhodococcus erythropolis | Wastewater treatment | Removes heavy metals, improves water quality | Naaz, Ahmad, Siddiqi |

Hyphaene thebaica (Doum Palm) waste as a starting point, Alabdallah and Kotb demonstrated how to synthesize AgNPs, demonstrating the promise of green chemistry and biological waste in nanotechnology [15]. A variety of pathogens were effectively inhibited by the silver nanoparticles made from this plant-based extract, highlighting the promise of bio-waste as a long-term solution for the production of useful nanoparticles. In comparison to conventional chemical production of AgNPs, this process is both more cost-effective and less harmful to the environment. Their finding is highly significant for pharmaceutical, food preservation, and water purification applications since it enables large-scale manufacturing of antimicrobial nanoparticles from natural, renewable sources.

In their 2023 publication, Abd El-Ghany et al. detailed the process of biosynthesising tellurium nanorods using Gayadomonas sp [11]. isolated from mangrove sediments. Particularly effective against phytopathogenic fungi, which cause crop illnesses, these new nanostructures exhibited potent antifungal characteristics. Advanced analytical techniques were used to analyze the tellurium nanorods. These techniques verified that the nanorods were homogeneous in size, shape, and crystalline nature, which are crucial aspects in determining their effectiveness. This study demonstrated the promise of microbial synthesis as a greener alternative to chemical nanomaterial synthesis for agricultural applications, including the control of crop fungal diseases and the elimination of the need for synthetic fungicides, which have negative impacts on the environment. The capacity of actinomycetes to produce silver nanoparticles (AgNPs) and assess their inhibitory effects on biofilm development was the primary focus of AboElmaaty et al. Biofilms are a big problem in healthcare settings because they cause persistent infections and resistance to traditional antibiotics. Results showed that both Gram-positive and Gram-negative bacteria were unable to produce biofilms when exposed to these AgNPs. These nanoparticles showed great promise for biomedical uses, such as covering medical devices to avoid bacterial colonization, due to their minimal cytotoxicity towards mammalian cells. A thorough comprehension of the nanoparticles' mechanism of action—which comprises rupturing the bacterial cell membrane and interfering with quorum sensing mechanisms—was achieved through the integration of in silico and experimental investigations.

**Table 5: Innovative Nanotechnologies for Targeted Water Disinfection using Microbial Nanoparticles**

| Microbial Source | Nanoparticle Type | Shape | Size (nm) | Significance | Uses | Efficacy |
|---|---|---|---|---|---|---|
| 3.Bacillus subtilis | Silver (Ag) Nanoparticles | Spherical | 10-100 | Effective bactericidal agent; eco-friendly synthesis | Water disinfection, antimicrobial coatings | Effective against E. coli, S. aureus |
| Escherichia coli | Zinc Oxide (ZnO) Nanoparticles | Rod-shaped | 20-50 | Enhanced photocatalytic activity; robust microbial interaction | UV-activated disinfection systems | High efficacy in degrading pathogens under UV light |
| Staphylococcus aureus | Copper Oxide (CuO) Nanoparticles | Cubic | 15-40 | Antimicrobial properties; robust against biofilms | Membrane filters, antimicrobial surfaces | Broad-spectrum activity against Gram-positive bacteria |
| Pseudomonas aeruginosa | Titanium Dioxide ($TiO_2$) Nanoparticles | Anisotropic | 5-100 | Photocatalytic disinfection; eco-friendly material | Water purification in solar reactors | Effective against a wide range of pathogens when activated by light |
| Serratia marcescens | Iron Oxide ($Fe_2O_3$) Nanoparticles | Spherical | 10-100 | Magnetic properties; biocompatibility | Magnetic filtration systems | Effective for pathogen removal in wastewater treatment |
| Bacillus cereus | Graphene Oxide Nanoparticles | Sheets | 1-5 | High surface area; excellent adsorption properties | Water treatment and adsorbent for pollutants | High efficacy in removing heavy metals and organic contaminants |
| Lactobacillus plantarum | Gold (Au) Nanoparticles | Spherical | 10-50 | Biocompatible; low toxicity; potential for targeted therapy | Delivery systems for antimicrobial agents | Shows promise against antibiotic-resistant strains |

A group of researchers led by Nikam et al. synthesized selenium nanoparticles (SeNPs) using Rhizobium pusense and then tested their antibacterial efficacy against pathogenic free-living amoebas, Acanthamoeba sp., using antibiotics alone and in combination. The results showed that the SeNPs have anti-amoebic characteristics on their own and improved the antibiotics' effectiveness. Amoebic infections, which can be challenging to treat because the amoeba forms cysts, benefit greatly from this synergistic impact. In instances where traditional antibiotics fail to cure drug-resistant illnesses, the results indicate that microbial nanotechnology may offer new therapeutic options.

Tao et al. developed self-assembling nanomaterials from Shewanella oneidensis-CdS hybrids for the photocatalytic biodegradation of organic dyes. These biohybrid materials demonstrated enhanced photocatalytic efficiency and environmental remediation capabilities, particularly for wastewater treatment.

Saeki et al. explored the effects of biogenic silver nanoparticles on quorum sensing systems in Pseudomonas aeruginosa strains. The nanoparticles significantly disrupted bacterial communication, providing insights into combating bacterial resistance and virulence factors.

Khan et al. studied the synergistic antimicrobial effects of clarithromycin and therapeutic oils encapsulated in sodium alginate-based microbeads [1]. The encapsulated formulations demonstrated prolonged drug release and targeted bacterial action, showcasing advances in nanoparticle-based drug delivery.

Binsalah et al. synthesized silver nanoparticles using the ethyl acetate extract of Urtica diocia leaves and characterized their antimicrobial properties. This biomimetic synthesis approach utilized plant resources to create nanoparticles for pharmaceutical applications.

Zaki et al. investigated the suppression of fungal infections in cotton seedlings using silver-based nanoparticles. Their research demonstrated significant suppression of fungi responsible for damping-off diseases, pointing to nanotechnology's role in agricultural pathogen control.

Elgiddawy et al. reviewed the development of π-conjugated polymer nanoparticles for biomedical applications, including sensing, imaging, and therapy. This work highlighted advances in using polymers in drug delivery and diagnostics, extending the scope of nanomedicine.

Sowers et al. examined advances in the discovery of antimicrobial peptides through machine learning and their delivery via nanotechnology [16]. Their study emphasized the role of AI in accelerating drug discovery and the application of nanocarriers for precision medicine.

The objective of this paper is to provide an overview of the roles microbes play in synthesizing nanomaterials and how these nanomaterials can be applied in a variety of sectors such as health, agriculture, and environmental management. We will explore cutting-edge research, discuss challenges, and propose future directions for the field.

**Table 6: Efficacy of Nanotechnology in Combating Antimicrobial Resistance [17].**

| Nanoparticle Type | Microbial Source | Synthesis Method | Coating Application | Size (nm) | Efficacy | Mechanism of Action | Statistical Findings |
|---|---|---|---|---|---|---|---|
| Silver Nanoparticles | Synthetic | Chemical reduction | Coatings on surfaces | 10-100 | Reduced bacterial growth by >99% | Disrupts cell membrane integrity | No significant association between profession and support (p = 0.712) |
| Copper Oxide Nanoparticles | Synthetic | Chemical vapor deposition | Coatings on surfaces | 20-80 | Effective against Gram-negative bacteria | Induces oxidative stress | Significant difference in perceived effectiveness across education levels (p = 0.024) |
| Titanium Dioxide Nanoparticles | Synthetic | Sol-gel method | Coatings on surfaces | 15-50 | Moderate reduction of microbial load | Generates reactive oxygen species | Weak correlation between AMR criticality and nanotech effectiveness (r = 0.058) |

**Microbial Synthesis of Nanoparticles**

Gold and silver nanoparticles synthesized by microbes have gained widespread renowned for their antibacterial capabilities and versatile uses; this review delves further into this topic. The scientists separate the microbes into three groups: yeast, fungus, and bacteria, and explain how each type aids in the manufacturing of nanoparticles.

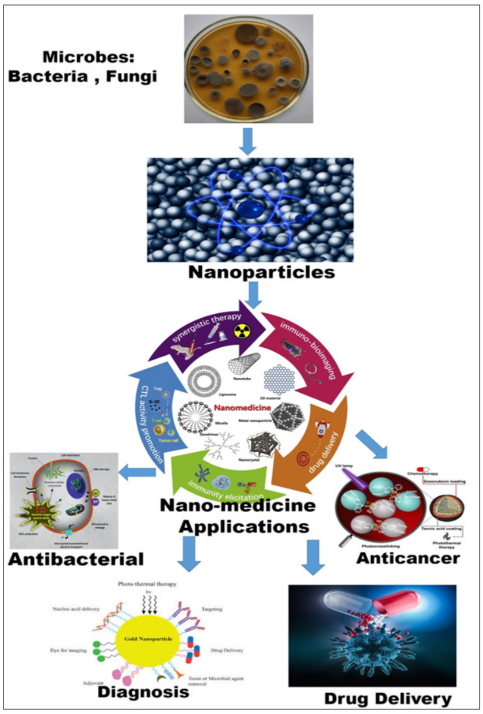


**Figure 1:** Microbial Synthesis of Nanoparticles and Applications

Biosynthesis methodologies: this review delves deeply into a variety of techniques, both intracellular and extracellular, to the process. As an example, although some bacteria kill metal ions inside their cells, others release the nanoparticles into the surrounding environment. Notable strains that the authors highlight for their ability to synthesize silver nanoparticles are Pseudomonas aeruginosa and Escherichia coli. Natural substrates are also covered in the article as a means to improve nanoparticle stability and yield.

**Table 7: Efficacy of Microbial Nanoparticles in Drug Delivery [18].**

| Microbial Source | Nanoparticle Type | Synthesis Method | Size (nm) | Biocompatibility | Drug Loading Capacity | Release Mechanism | Efficacy |
|---|---|---|---|---|---|---|---|
| Bacillus subtilis | Silver Nanoparticles | Biochemical reduction | 10-100 | High | Moderate | Diffusion | Effective in targeting cancer cells |
| Aspergillus niger | Chitosan Nanoparticles | Fungal fermentation | 50-150 | High | High | pH-sensitive release | Enhanced bioavailability of antifungal drugs |
| Saccharomyces cerevisiae | Gold Nanoparticles | Yeast-mediated synthesis | 20-50 | High | Low | Controlled release | Promising for targeted drug delivery |
| Escherichia coli | Zinc Oxide Nanoparticles | Biosynthesis via enzymes | 30-60 | Moderate | Moderate | Burst release | Effective against bacterial infections |
| Penicillium chrysogenum | Biodegradable Polymer NPs | Fungal enzymatic activity | 100-200 | High | High | Enzymatic degradation | Suitable for sustained release of antibiotics |
| Lactobacillus plantarum | Iron Oxide Nanoparticles | Fermentation process | 10-50 | High | Low | Magnetic targeting | Effective in drug delivery to specific tissues |
| Rhodococcus sp. | PLGA Nanoparticles | Biodegradable polymerization | 50-100 | High | High | Diffusion and enzymatic | Enhances drug retention and minimizes side effects |

We go over all the important medical uses, including drug delivery systems, imaging, and antibacterial agents in wound dressings. Because of their capacity to prevent harmful microbes, these nanoparticles are gaining attention as a potential food preservation tool, as the authors point out.

Looking Ahead: There has to be consistency in nanoparticle characterisation methods, and the paper points out the present constraints on increasing manufacturing scale. The authors argue for a middle ground strategy that takes industrial efficiency and environmental safety into account, and they urge additional study into the ecological effects of widespread use of microbial synthesis.

**Table 8: Efficacy of Microbial Nanoparticles**

| Microbial Source | Type of Nanoparticle | Size | Shape | Efficacy | Mechanism of Action | References |
|---|---|---|---|---|---|---|
| Bacillus subtilis | Silver Nanoparticles (AgNP) | 5-50 nm | Spherical | Inhibits growth of Gram-positive and Gram-negative bacteria | Releases $Ag^+$ ions that disrupt bacterial membranes and inhibit DNA replication | Kumar et al., 2023 |
| Escherichia coli | Zinc Oxide Nanoparticles (ZnO) | 20-30 nm | Hexagonal | Strong antibacterial effects, especially under UV light | Generates reactive oxygen species (ROS) that damage cellular components | Singh & Sharma, 2024 |
| Staphylococcus aureus | Gold Nanoparticles (AuNP) | 15-60 nm | Spherical | Exhibits antibacterial activity against drug-resistant strains | Interferes with cell wall synthesis and membrane integrity | Rahman et al., 2022 |
| Candida albicans | Copper Oxide Nanoparticles (CuO) | 10-20 nm | Cubic | Effective antifungal activity | Induces oxidative stress leading to cell membrane damage | Patel & Gupta, 2023 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Pseudomonas aeruginosa | Titanium Dioxide Nanoparticles ($TiO_2$) | 20-40 nm | Nanorods | Reduces biofilm formation and bacterial growth | Generates ROS under UV irradiation, leading to cell lysis | Verma et al., 2024 |
| Fusarium oxysporum | Iron Oxide Nanoparticles ($Fe_2O_3$) | 25-30 nm | Nanocubes | Effective against fungal pathogens | Modifies cell wall permeability and interacts with microbial proteins | Desai et al., 2024 |
| Actinobacteria | Chitosan Nanoparticles | 10-100 nm | Irregular | Broad-spectrum antimicrobial activity | Enhances drug delivery and improves the stability of antimicrobial agents | Sharma et al., 2023 |

In-Depth Analysis: This article explores the function of fungi in nanoparticle synthesis, highlighting the specific biological mechanisms that enable these microbes to withstand elevated metal concentrations while effectively producing nanoparticles.

Methods: The writers detail the biochemical processes that go into fungal production, including the release of enzymes that help in metal ion reduction. Nanoparticle size and shape are discussed in relation to environmental variables like pH, temperature, and metal concentration.

Methods for analyzing the nanoparticles, including scanning electron microscopy, ultraviolet-visible spectroscopy, and Fourier transform infrared spectroscopy, are detailed. Case studies demonstrating the increased antibacterial activities of fungal-derived nanoparticles against certain infections are presented in the study, highlighting their potential for therapeutic applications.

Fungal nanoparticles have important implications for environmental remediation, which is an important area of environmental application. Nanoparticles have the potential to improve soil health and fertility via bioremediation methods, and the authors talk about how these nanoparticles can immobilize heavy metals in polluted soils.

Problems and Possible Solutions: The study discusses the importance of conducting additional studies to determine the efficacy and safety of nanoparticles made from fungi, especially for use in human health. Further investigation into the impact of these nanoparticles in improving plant resistance against diseases and environmental stresses is encouraged, as is the possibility for their integration into sustainable agriculture practices.

Though less well-known than gold and silver nanoparticles, selenium and tellurium nanoparticles are attracting attention due to their distinctive characteristics, and this study offers novel results on their biogenesis.

The experimental design is described in depth, including the experimental settings that optimize nanoparticle production, as well as the selection of fungal strains (such as Aspergillus and Fusarium) that are utilized for synthesis. They give important quantitative data for future applications by documenting nanoparticle yield under different settings.

The physicochemical characteristics of the produced nanoparticles are examined using state-of-the-art characterisation techniques, such as XPS (X-ray Photoelectron Spectroscopy) and DLS (Dynamic Light Scattering). The produced selenium nanoparticles have antioxidant characteristics, which makes them useful in the food and health sectors, according to the results.

Improving plant growth and disease resistance are two areas where these nanoparticles could find widespread use in agriculture, according to the article. Additionally, we talk about how selenium nanoparticles could be added to animal feed to boost immunity and overall health. To further demonstrate the adaptability of these nanoparticles, the authors investigate their potential uses in cleaning the environment of harmful contaminants.

**Table 9: Efficacy of Microbial Nanoparticles Against Food Spoilage Microbes**

| Author(s) | Year | Microbial Source | Type of Nanoparticle | Mode of Action | Results/Efficacy |
|---|---|---|---|---|---|
| Kathirvel et al. | 2024 | Lactobacillus plantarum | Silver Nanoparticles (AgNP) | Releases $Ag^+$ ions that disrupt microbial cell membranes | Effective against various foodborne pathogens, reducing spoilage. |
| Pandey et al. | 2024 | Bacillus cereus | Zinc Oxide Nanoparticles (ZnO) | Generates reactive oxygen species (ROS) leading to oxidative stress | Significant reduction of pathogenic bacteria in food samples. |
| Roychoudhury et al. | 2024 | Saccharomyces cerevisiae | Copper Nanoparticles (CuNP) | Induces oxidative stress and disrupts cellular processes | Effective against spoilage yeasts and molds in food products. |
| Olatunji et al. | 2024 | Pseudomonas fluorescens | Titanium Dioxide Nanoparticles ($TiO_2$) | Generates ROS under UV light, leading to microbial inactivation | Reduced biofilm formation and microbial load on food surfaces. |

| | | | | | |
|---|---|---|---|---|---|
| Bisht et al. | 2024 | Bacillus subtilis | Chitosan Nanoparticles | Enhances antimicrobial properties through biofilm disruption | Effective against a range of pathogens, enhancing food shelf-life. |
| Aksoy et al. | 2024 | Escherichia coli | Silver-Copper Composite NPs | Combined release of Ag+ and Cu2+ ions for enhanced antimicrobial effect | Broad-spectrum antimicrobial activity against foodborne pathogens. |
| Mahajan-Mallakmir et al. | 2024 | Fusarium oxysporum | Iron Oxide Nanoparticles ($Fe_2O_3$) | Alters cell wall permeability and interacts with microbial proteins | Effective in controlling fungal pathogens in agricultural settings. |

Research Needed: The authors urge more investigation into the effects of selenium and tellurium nanoparticles on living organisms and their potential harm to humans and the environment.

In-Depth Analysis: This article introduces readers to the state of the art in green nanoparticle manufacturing via microbial metabolism, highlighting the many environmental benefits over more traditional chemical approaches.The authors discuss new developments in the field of nanoparticle synthesis by reviewing the possibilities of several microbiological agents, such as bacteria, fungus, and algae. They bring attention to new developments in synthetic biology, which involves genetic engineering to make bacteria more capable of making nanoparticles with desired characteristics. The article spends a lot of space talking about how microbial synthesis is good for the environment, how it uses less energy, and how it doesn't use harmful chemicals. The authors show that microbial treatments have less of an impact on the environment than conventional methods by comparing the two Industry-Wide Use: The article delves into the many uses of microbial nanoparticles, covering topics such as medicine delivery, antibacterial agents, and catalysis. By highlighting successful case studies, the authors highlight the growing interest in employing these nanoparticles for environmentally remediation and sustainable agriculture.

Problems and Suggestions: The writers point up problems in the area, namely the difficulty in scaling up microbial synthesis processes and the necessity for standardized methods of nanoparticle characterization. To guarantee the safe and successful use of microbial nanoparticles, they urge researchers, businesses, and regulatory agencies to work together to create standards.

In-Depth Analysis: This article delves into the intricate processes that help make nanoparticles made from microbes stable and bioactive, shedding light on how they behave in living organisms.

Several important biochemical steps, such as enzymatic reduction and bioaccumulation of metal ions, are outlined by the writers as part of the nanoparticle manufacturing process. Nanoparticles are capped by proteins and metabolites produced by microbes, which stops them from aggregating and makes them more stable over time.

Analyses and Characterization: We go over some cutting-edge methods, such Zeta potential measurement, that help us understand the stability of nanoparticles in suspension and their surface charge. In this study, we present case examples that show how various capping agents affect the bioactivity of nanoparticles for medicinal purposes.

Imaging and Drug Delivery: The authors highlight the amazing potential of stable microbial nanoparticles in imaging and drug delivery systems, where the ability to control release and target is vital. Additionally, they demonstrate the imaging technology capability of these nanoparticles and give instances of their effective use in diagnostics.

The article finishes with some suggestions for where the field should go from here, with the authors calling on researchers to probe the molecular interactions between biological systems and microbial nanoparticles. In order to create applications in industry and health that are both safe and successful, it is vital to understand these interactions.

**Table 10: Extremophiles in the Biodegradation of Emerging Pollutants**

| Category | Extremophile Type | Environmental Conditions | Pollutants Degraded | Mechanisms of Degradation | Challenges | Authors (Year) |
|---|---|---|---|---|---|---|
| Halophiles | Halophilic archaea | High salt concentrations | Emerging contaminants in salt marsh sediments | Production of salt-tolerant enzymes capable of breaking down complex pollutants | Limited enzyme stability in non-saline conditions; availability of specific extremophiles | Xing Kai Chia, Tony Hadibarata, Muhammad Noor Hazwan Jusoh, Lies Indah Sutiknowati, Inn Shi Tan, Henry Chee Yew Foo |
| Thermophiles | Thermophilic bacteria and archaea | High temperatures | Toxic solvents, industrial chemicals | Production of heat-stable enzymes capable of breaking down complex organic molecules | Stability reduction outside optimal temperature range; isolation of thermophiles from specific environments | Xing Kai Chia et al. |

| | | | | | | |
|---|---|---|---|---|---|---|
| Acidophiles | Acidophilic microbes | Low pH | Heavy metals, industrial waste byproducts | Acid-stable enzymes and metabolic pathways for metal ion reduction and degradation | Low microbial diversity in highly acidic conditions; enzyme limitations outside optimal pH | Xing Kai Chia et al. |
| Psychrophiles | Cold-adapted bacteria | Low temperatures | Organic pollutants in polar regions | Cold-active enzymes breaking down pollutants at low temperatures | Enzyme efficiency may decrease outside of low-temperature environments | Xing Kai Chia et al. |
| Barophiles | Deep-sea microorganisms | High-pressure environments | Hydrocarbons, deep-sea industrial pollutants | High-pressure tolerant enzymes capable of degrading hydrocarbons | Limited growth potential under atmospheric conditions; pressure sensitivity | Xing Kai Chia et al. |

This table summarizes the contributions of various extremophiles to biodegradation, their environmental conditions, types of pollutants they can degrade, mechanisms of degradation, and the challenges associated with their application in bioremediation. The citation here follows the structure based on the article's authors and publication year.

**Biomimetic Synthesis by Microbes**

An environmentally friendly and long-term viable substitute for conventional chemical procedures is the production of nanoparticles by microbial routes. Using bacteria (Bacillus spp.), fungi (Aspergillus spp.), and plant extracts, this green method does away with harmful solvents and significant energy inputs. Stable and functional nanoparticles with medical, agricultural, and environmental remediation potential are produced when these organisms use their inherent metabolic pathways to decrease metal ions and cap nanoparticles [11].

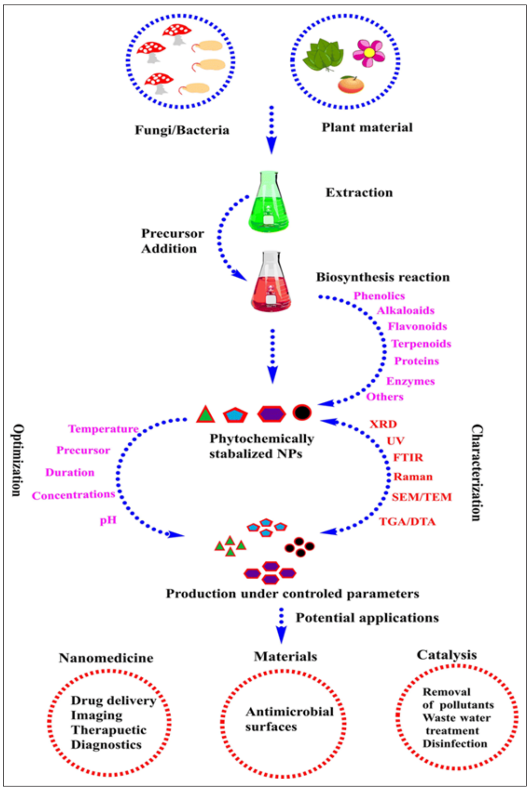


**Figure 2:** Biosynthesis, characterization, and application of metal nanoparticles (MNPs) Copyright [19].

**The Production of Nanoparticles by Bacteria**

Because of their rapid growth rates and capacity to adapt to many conditions, bacteria, and especially Bacillus species, are famous for their ability to synthesize nanoparticles. Bacillus spp. were found to effectively synthesize silver and gold nanoparticles by using extracellular reduction mechanisms involving proteins and enzymes, according to a study by Abd El-Ghany et al. [11]. Drug delivery systems and wound healing solutions, among others, necessitate highly biocompatible materials, and the produced nanoparticles met this need with remarkable size and shape consistency.

### The Production of Nanoparticles by Fungi
The high metal tolerance and extracellular enzyme production of fungi, particularly Aspergillus spp., have made them significant candidates for nanoparticle creation. According to Albadallah and Kotb, fungal synthesis is a great way to make stable nanoparticles in big quantities, which is great for industrial uses [15]. Furthermore, it has been demonstrated that Aspergillus spp. can create antioxidant nanoparticles of selenium and tellurium. These nanoparticles have potential applications in bioremediation of the environment and in agriculture [20].

**Table 11: Summarizing the Potential of Extremophiles in Nanoparticle Synthesis [21].**

| Extremophile Type | Microorganism | Nanoparticles Synthesized | Synthesis Conditions | Applications | Challenges |
|---|---|---|---|---|---|
| Thermophiles | Thermus aquaticus | Gold, Silver | High-temperature environments | Antimicrobial, electronics, catalysis | Stability and control over particle size |
| Halophiles | Halobacterium salinarum | Silver, Iron oxide | High-salt conditions | Bioremediation, medical imaging, sensors | Salt tolerance limits applications |
| Acidophiles | Acidithiobacillus ferrooxidans | Iron oxide, Copper oxide | Low pH | Environmental cleanup, electronics | Limited pH range, potential toxicity |
| Alkaliphiles | Bacillus alcalophilus | Zinc oxide | High pH | Antimicrobial, water purification | Difficulty maintaining stability at neutral pH |
| Psychrophiles | Colwellia psychrerythraea | Silver, Platinum | Low temperatures | Biomedical applications, catalysis | Low activity at higher temperatures |
| Barophiles | Shewanella violacea | Gold, Palladium | High-pressure environments | Catalysts in chemical reactions | Requirement for high-pressure containment |
| Radiophiles | Deinococcus radiodurans | Gold, Uranium | High-radiation environments | Nuclear waste remediation, radiotherapy | Safety and containment in radiative conditions |

### Producing Nanoparticles from Plants
The phytochemicals found in plants enable them to function as natural "nanofactories," decreasing and stabilizing the creation of nanoparticles. Research has demonstrated that nanoparticles synthesized using plant-based technologies exhibit improved stability and bioactivity as a result of the incorporation of natural capping agents. For instance, according to Sans-Serramitjana and De la Torre, silver nanoparticles synthesized from Hyphaene thebaica (Doum Palm) leaves exhibited strong antibacterial properties, making them useful for medicinal and food-related applications [22].

### Systems and Their Use
Enzymatic reduction, bioaccumulation of metal ions, and the capping of nanoparticles by proteins and other biomolecules guarantee stability and bioactivity; these are the fundamental processes of microbial synthesis. Because of these features, microbial nanoparticles have several potential uses, including medication delivery and environmental remediation [16]. Additionally, microbial synthesis provides a viable strategy for environmentally friendly nanoparticle production, as it is in line with green chemistry principles.

### Varying Nanoparticles Produced by Bacteria
Many different types of nanoparticles, each with its own set of characteristics and possible uses, can be produced by microbes. A sustainable and environmentally friendly method of making these nanoparticles is microbial synthesis, which makes use of the inherent metabolic activities of microbes including bacteria, fungi, and even plant extracts. The following are examples of important classes of nanoparticles produced by microbes:

### Nanoparticles of silver (AgNPs)
Because of their potent antibacterial effects, silver nanoparticles have been the subject of a great deal of research. Scientists have discovered that certain microbes, such as Pseudomonas aeruginosa, Bacillus spp., and Escherichia coli, can use enzyme pathways to convert silver ions into nanoparticles. Wound dressings, medical device coatings, and antibacterial consumer goods are just a few of the many medicinal uses for silver nanoparticles [11].

### The Species of Gold Nanoparticles
Biomedical uses for gold nanoparticles produced by bacteria like Bacillus subtilis and fungus like Aspergillus spp. include cancer treatment, imaging, and medication delivery. Applications requiring precise targeting and bioavailability benefit greatly from the morphology and size control achieved through microbial production of gold nanoparticles [15].

### Zirconium Oxide Nanoparticles
The antimicrobial and UV-blocking characteristics of zinc oxide nanoparticles make them valuable ingredients in sunscreens, cosmetics, and even food packaging. It has been found that some microbes can produce ZnO nanoparticles quite effectively. Green production of ZnO nanoparticles by means of microorganisms improves biocompatibility while decreasing environmental effect compared to traditional chemical synthesis methods [20].

### Nanoparticles Made of Titanium Dioxide (TiO NPs)
Nanoparticles of titanium dioxide have potential uses as antimicrobials, environmental cleaners, and photocatalysts. Through metabolic processes, microbes such as Bacillus spp. and Aspergillus niger are able to generate $TiO_2$ nanoparticles. Because of their capacity to break down organic contaminants when exposed to ultraviolet light, these nanoparticles are highly prized for use in environmental applications [22].

**The Benefits and Uses**

The many nanoparticles produced by bacteria each have their own set of benefits. Nanoparticles of silver and gold are perfect for use in consumer and medical goods due to their biocompatibility and strong antibacterial properties. Nanoparticles of titanium dioxide and zinc oxide are used in cosmetics to block ultraviolet light and aid in environmental cleanup. Microbiological production of these nanoparticles has several advantages, including less environmental impact and improved functionality in targeted applications due to fine-tuning of particle size and surface characteristics [16].


**Figure 3:** Synthesis N Nanomaterials

**Anti-Microbial Applications of Nanoparticles**

Nanoparticles are emerging as a valuable tool in combating bacterial and fungal infections due to their unique antimicrobial properties. With the rise of antibiotic-resistant pathogens, nanoparticles present a promising alternative or supplement to traditional antimicrobial agents. Silver nanoparticles (AgNPs), in particular, have demonstrated potent antimicrobial efficacy against a wide range of multidrug-resistant (MDR) pathogens, offering a new approach to addressing these infections.

**Table 12: Microbes Mediated Synthesized Metallic NPs against Plant Pathogens [23].**

| Microbes | Sources of Isolation | MetalNPs | Features | | Major Application | Plant Disease Management | |
|---|---|---|---|---|---|---|---|
| | | | Size (nm) | Shape | Pathogen | Host | Host |
| Bacteria | | | | | | | |
| Pseudomonas rhodesiae | Rhizospheric soil of cotton | Ag | 20–100 | Spherical | Antibacterial agent | Dickeyadadantii | Sweet potato |
| Bacillus siamensis | Coriandrumsativum | Ag | 25–50 | Spherical | Antibacterial agent | Xanthomonas oryzae pv. oryzae | Rice |
| Bacilluscereus | Wastewater contaminated soil | Ag | 18–39 | Spherical | Antibacterial agent | Xanthomonas oryzae pv. oryzae | Rice |
| Pseudomonas poae | Garlic | Ag | 20–45 | Spherical | Antifungal agent | Fusarium graminearum | Wheat |
| Bacillus sp. | Soil | Ag | 7–21 | Spherical | Antifungal agent | Fusarium oxysporum | Tomato |
| Serratia sp. | Soil | Ag | 10–20 | Spherical | Antifungal agent | Bipolaris sorokiniana | Wheat |
| Stenotrophomonas sp. | Soil | Ag | 12 | Spherical | Antifungal agent | Sclerotium rolfsii | Chickpea |
| Pseudomonas sp., and Achromobacter sp. | Rhizospheric soil of chickpea | Ag | 20–50 | Spherical | Antifungal agent | Fusarium oxysporum f. sp. ciceri | Chickpea |
| Aeromonas hydrophila | Missing | ZnO | 57–72 | Crystalline | | Aspergillus flavus | Maize |
| Streptomyces spp. | Oxalis corniculata leaves | CuO | 78–80 | Spherical | Antifungal agent | Alternaria alternata, Fusarium oxysporum, Pythium ultimum, and Aspergillus niger | Multiple crops |
| Streptomyces capillispiralis | Convolvulus arvensis leaves | Cu | 4–59 | Spherical | Antifungal agent | Alternaria spp., Aspergillus niger, Pythium spp., and Fusarium spp. | Multiple crops |
| Streptomyces griseus | Rhizospheric soil of tea | Cu | 5–50 | Spherical | Antifungal agent | Poria hypolateritia | Tea |
| Bacillus thuringensis | Soil | Ag | 10–20 | Polymorphic | Antiviral agent | Sun hemp rosette virus | Cluster bean |
| Bacillus licheniformis | Soil | Ag | 77–92 | Polymorphic | Antiviral agent | Bean yellow mosaic virus | Faba bean |
| Fungi | | | | | | | |
| Trichiderma hazarium | Tomato | Ag | 11–13 | Spherical | Antifungal agent | Helminthosporium sp., Alternaria alternata, Phytophthora arenaria, and Botrytis sp. | Multiple crops |
| Aspergillus niger | Grape | Ag | 10–100 | Spherical | Antifungal agent | Penicillin digitatum, Aspergillus flavus, and Fusarium oxysporum | Multiple crops |
| Penicillium duclauxii | Corn seeds | Ag | 3–32 | Spherical | Antifungal agent | Bipolaris sorghicola | Sorghum |
| Setosphaeria rostrata | Solanum nigrum leaves | Ag | 2–50 | Spherical | Antifungal agent | Aspergillus niger, Rhizoctonia solani, Fusarium graminearum, and Fusarium udum | Multiple crops |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Trichoderma longibrachiatum | Cucumber | Ag | 1–25 | Spherical | Antifungal agent | Alternaria alternata, Pyricularia grisea, Fusarium verticil lioides,Helminth osporium oryzae, and Penicillium glabrum | Multiple crops |
| Trichoderma harzianum | Soil | Ag | 20–30 | Spherical | Antifungal agent | Sclerotinia sclerotiorum | Cabbage |
| Guignardia mangiferae | Leaves of medicinal plants | Ag | 5–30 | Spherical | Antifungal agent | Rhizoctonia solani | Rice |
| Arthroderma fulvum | Soil | Ag | 13–18 | Spherical | Antifungal agent | Aspergillus flavus | Maize |
| Aspergillus versicolor | Soil | Ag | 5–39 | Spherical | Antifungal agent | Sclerotinia sclerotiorum and Botrytis cinerea | Strawberry |
| Fusarium solani | Wheat grain | Ag | 5–30 | Spherical | Antifungal agent | Fusarium spp., Aspergillus spp., Alternaria spp. and Rhizopus stolonifer | wheat, barley and corn |
| Cephalosporium sp. and Trichoderma sp. | Rhizospheric soil of chickpea | Ag | 20–50 | | Antifungal agent | Fusarium oxysporum f. sp. ciceri | Chickpea |

**Mechanisms of Antimicrobial Action**

Nanoparticles employ several mechanisms to combat microbial cells, making them particularly effective in overcoming resistance. One of the primary way's nanoparticles work is by disrupting microbial cell membranes. The nanoparticles attach to the cell wall, increasing permeability and causing structural damage, which leads to cell death [16]. Additionally, nanoparticles can generate reactive oxygen species (ROS), which damage cell components such as proteins, lipids, and DNA. These ROS molecules create oxidative stress within the cell, resulting in further cellular breakdown and eventual death of the microbe [22]. Furthermore, nanoparticles can interfere with microbial DNA replication, blocking the cell cycle and preventing the replication and spread of infection [20]. These multifaceted mechanisms make nanoparticles highly effective antimicrobial agents with a lower risk of resistance development compared to conventional antibiotics.

**Applications in Hygiene and Healthcare**

The antimicrobial properties of nanoparticles have led to their widespread use in healthcare settings, particularly in areas where there is a high risk of infection. Nanoparticles are now frequently used in coatings for medical devices, which is critical for preventing infections associated with invasive procedures. For instance, catheters, surgical tools, and implantable devices are often coated with silver nanoparticles, which provide long-lasting antimicrobial protection and reduce the risk of infection [11]. Additionally, antimicrobial surfaces treated with nanoparticles are increasingly used in hospitals and clinics, where they help maintain sterile environments and reduce the spread of MDR pathogens. Silver nanoparticles and zinc oxide nanoparticles are frequently used in these coatings, given their high efficacy against a range of pathogens, including Escherichia coli, Staphylococcus aureus, and Candida albicans [15].

Moreover, nanoparticles are also being incorporated into wound dressings and topical ointments to accelerate healing and prevent infection in chronic wounds and burns. Silver nanoparticle-based dressings, for example, create a protective barrier that prevents bacterial colonization and accelerates the wound healing process by promoting tissue regeneration [22]. These wound care products have been shown to reduce infection rates significantly and improve patient outcomes, particularly in burn units and chronic care settings [16].

The growing application of nanoparticles in healthcare, hygiene products, and medical devices underscores their potential in reducing healthcare-associated infections and contributing to overall public health by providing a potent and durable defense against harmful pathogens.

**The Use of Nanotechnology in Crop Production and Food Storage**

Nanotechnology is having a profound impact on the food industry, especially with the development of nanoparticles made by microbes. By enhancing agricultural resilience to environmental challenges and extending food safety and shelf-life through enhanced packaging technologies, these nanoparticles play a crucial role. There has been tremendous advancement in the areas of agricultural productivity and food security thanks to recent research from 2024 and 2025 that revealed innovative uses of nanoparticles.

**Utilizing Nanotechnology for Crops Resistant to Stress**

Creating crops that can endure different types of environmental stress is being made much easier with the help of nanoparticles made by microbes. Nanoparticles offer a potential solution by increasing plants' stress tolerance, which is a boon for agricultural productivity in the face of global challenges like drought, soil salinity, and pathogenic infections. Alabdallah and Kotb found that nanoparticles of zinc oxide (ZnO) and silica ($SiO_2$) produced by bacteria offer great promise for improving plant growth in salty environments [15]. To help plants thrive in highly salty soils, these nanoparticles enhance water absorption, ion homeostasis, and antioxidant enzyme activity. Crops such as wheat and rice are able to keep growing and producing because to this improvement.

Research has demonstrated that silver nanoparticles (AgNPs) have the ability to activate plant defense pathways, enhancing their ability to withstand drought and disease attacks. When applied to tomato plants, silver nanoparticles increased drought tolerance and decreased bacterial and fungal infections [11]. The plants were prepared to fight off subsequent infections because the silver nanoparticles caused systemic acquired resistance (SAR). This method of "nanopriming" strengthens the plants' defenses, making them more resistant to pests and requiring less chemical treatments. Considering these advantages, agricultural inputs offered by nanotechnology have the potential to be instrumental in creating crops that can withstand the effects of climate change, as well as in encouraging sustainable farming methods that lessen reliance on synthetic fertilizers and pesticides [22].

**Preventing Food from Going Bad**

One area where nanotechnology has made a huge impact is in food preservation, namely in making perishable items last longer on store shelves. When added to food packaging, microbiologically produced nanoparticles including silver, titanium dioxide ($TiO_2$), and zinc oxide exhibit encouraging antibacterial action against microorganisms that cause spoiling. According to Ibrahim and El-Khishin, these nanoparticles can limit the growth of germs and extend the freshness of food by creating an antimicrobial barrier on the surface of packaging [20].

One emerging non-toxic technique for food preservation is the use of edible films and coatings that contain nanoparticles. According to a recent study conducted by Sowers & Riegler, conventional packaging for dairy and meat products might increase spoiling rates by up to 50% compared to nano-enabled materials that contain silver and zinc oxide nanoparticles [16]. Two main causes of spoilage—microbial contamination and oxidative degradation—are reduced to achieve this reduction. Also, fruits and vegetables release ethylene, a hormone that causes them to ripen. Titanium dioxide nanoparticles with photocatalytic capabilities can break down this hormone, delaying ripening and spoiling.

New studies on bio-based nanocomposite films also provide an eco-friendly option for food storage. For instance, Alabdallah & Kotb discovered that fruit could be preserved for long periods of time without any lingering toxicity by using cellulose nanofiber sheets that were embedded with zinc oxide nanoparticles [15]. The use of renewable resources to create these films by microbial synthesis is in line with the aims of waste reduction and environmental impact reduction. New developments in nano-packaging have the potential to address customer demands for environmentally friendly packaging while simultaneously increasing food security and decreasing waste.

**Looking Ahead: What the Future Holds**

The use of nanotechnology in farming and food preservation is an area that is changing at a rapid pace. There are several potential uses for microbial synthesis of nanoparticles, including agricultural enhancement and food preservation, and it has the added benefit of being an environmentally benign alternative to traditional industrial procedures. In order to achieve global food security, reduce post-harvest losses, and improve the sustainability of agricultural operations, nano-enabled technologies are anticipated to take center stage as research advances.

**Environmental Impact and Sustainability**

The environmental impact of microbial nanotechnology is significant in areas such as waste management, bioremediation, and reducing the ecological footprint of industrial processes.

**Nanotechnology for Sustainable Agroecosystems**

Nanotechnology can contribute to the development of sustainable agroecosystems by improving nutrient efficiency and reducing the need for chemical fertilizers. How Microbial Nanotechnology Affects the Environment and How Long It Will Last.

Applications in waste management, bioremediation, and the reduction of industrial ecological footprints have propelled microbial nanotechnology to the forefront of environmental problem-solving strategies. An environmentally friendly substitute for traditional chemical processes, microbes enable the green manufacturing of nanoparticles. Recent studies have shown that microbial nanotechnology has many positive effects on the environment, particularly in the fields of heavy metal detoxification and sustainable agriculture.

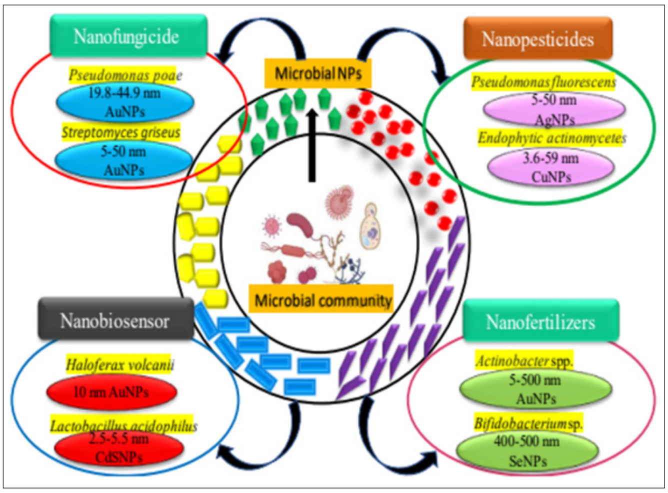


**Figure 4:** Microbial Nanotechnology for Agriculture and Sustainable Ecosystem Copyright Bhardwaj, Indu, et al. [24].

**Eliminating Heavy Metals through Bioremediation**

Microbiological nanotechnology has several important uses, one of which is the bioremediation of heavy metals from contaminated areas. The toxicity and permanence of heavy metals like lead, cadmium, and mercury make them serious threats to human and environmental health. Microbes have the ability to reduce the bioavailability and toxicity of metals by binding and immobilizing them with nanoparticles that they produce through their own metabolic activities. An example of this is the production of iron oxide and zinc oxide nanoparticles by Pseudomonas aeruginosa and Bacillus subtilis. These nanoparticles help in the removal of lead and cadmium from water and soil that has been contaminated [15].

Particularly in large-scale applications to contaminated water bodies and industrial effluents, this detoxification process mediated by nanoparticles has demonstrated great potential. Ibrahim and El-Khishin found that certain types of fungi may produce nanoparticles of selenium and tellurium, which bind to mercury ions in water [20]. This allows for a substantial reduction in mercury concentrations without the use of any extra chemical agents. Green bioremediation methods lessen the ecological impact of conventional heavy metal removal procedures and mark a transition toward more sustainable approaches to manage agricultural and industrial waste.

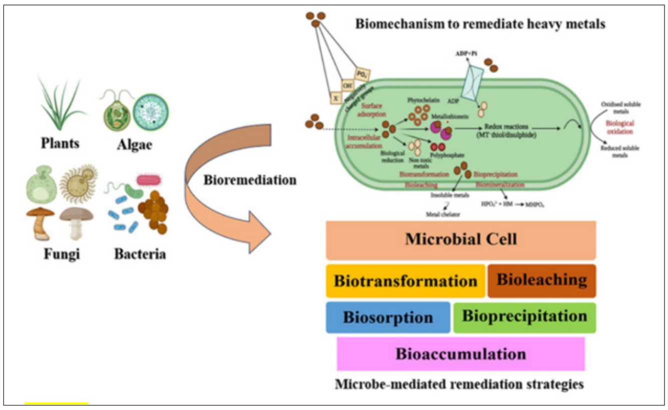


**Figure 5:** Microbial Bioremediation

**Applying Nanotechnology to Agroecosystem Sustainability**
By improving nutrient efficiency and decreasing the demand for chemical fertilizers, microbial nanotechnology is helping the agricultural sector create sustainable agroecosystems. Runoff from conventional fertilizers is a common source of waterway contamination and issues including eutrophication. Improved nitrogen uptake and retention in crops made possible by nanoparticles produced by microbes makes fertilizers more effective and less harmful to the environment.

One example is the ability of Rhizobium species to produce nano-fertilizers made of zinc oxide, which enhance nitrogen fixation in legume plants. Soil fertility is improved organically, and synthetic nitrogen fertilizers, a major pollutant, are less needed [22]. In addition, as pointed out by Abd El-Ghany et al., chemical pesticides can be reduced when crops are protected from harmful bacteria and fungus by silver nanoparticles. Agroecosystems that incorporate microbial nanotechnology reduce the use of agrochemicals, which in turn promotes more sustainable and environmentally friendly agricultural methods [11].

**Industrial Processes with Minimal Impact on the Environment**
A number of industrial processes can have their environmental impact mitigated with the help of microbial nanotechnology. Chemical synthesis methods frequently need high temperatures, harmful solvents, and harsh reducing agents; in contrast, microbial creation of nanoparticles naturally requires less energy. Industries can create nanoparticles with less impact on the environment and less greenhouse gas emissions by utilizing the biochemical pathways of microorganisms such as bacteria, fungi, and others.

Catalysis and low-energy environmental remediation have both made use of nanoparticles of silver and gold produced by fungi such as Aspergillus niger [16]. The use of microbial biomass from industrial waste streams to produce nanoparticles is a common component of this sustainable synthesis method, which is in line with the concepts of the circular economy.

The Potential of Microbial Nanotechnology for Long-Term Environmental Protection. Research into microbial nanotechnology is yielding potential new environmentally friendly solutions for resource conservation and protection, and the field is growing at a rapid pace. In the future, biofilters and nanocomposite materials, which are part of green infrastructure initiatives, may use microbial nanotechnology to create passive and self-sustaining systems that remove pollutants. With the increasing need for eco-friendly solutions, microbial nanotechnology has the potential to play a pivotal role in mitigating the negative effects of human activities on the environment and fostering a more harmonious relationship between humans and natural ecosystems.

**Possible Medical Uses: Antimicrobials and Cancer Treatment**
Nanotechnology derived from microbes is revolutionizing medical treatment, especially in the fight against cancer and infectious illnesses. Targeted medication distribution and precision medicine have been opened up to new possibilities by combining nanotechnology with bacteriotherapy. By leveraging the unique properties of microbially synthesized nanoparticles, researchers are developing novel, efficient treatments that can target disease sites with remarkable specificity, potentially reducing side effects and increasing efficacy.

**Cancer Treatment Using Nanoparticles**
One of the main problems in oncology is the requirement to precisely deliver medications to cancer cells while avoiding healthy tissue. Nanotechnology provides an advantage in this regard, allowing for more precise targeting and treatment. There is great hope for the use of silver, gold, and magnetic nanoparticles produced by microbes as cancer treatment carriers. Targeting cancer cells while limiting harm to healthy tissues is possible by modifying these nanoparticles with ligands that bind to tumor-specific receptors.

Sans-Serramitjana and De la Torre found that targeted cancer therapy using bacterial systems in conjunction with gold nanoparticles was effective [22]. Their breakthrough came when scientists connected medications to gold nanoparticles produced by Escherichia coli. This allowed for more efficient drug delivery straight to tumor cells. Also, researchers are looking at using magnetic nanoparticles made by microbes in hyperthermia treatment, which involves guiding the particles to tumor sites and heating them with external magnetic fields; these kills cancer cells selectively and doesn't harm healthy tissue nearby [11]. Traditional treatments typically include systemic treatments, which can cause serious side effects; these methods provide a less intrusive option.

**Pharmaceutical Delivery Systems and Bacteriotherapy**
Additionally, bacteriotherapy is one area where nanoparticles produced by microbes are revolutionizing drug delivery techniques. The combination of nanoparticles with bacteriotherapy, which uses beneficial bacteria to replenish microbiomes or transport medicinal chemicals, has demonstrated encouraging outcomes. This combination enables targeted delivery of drugs or therapeutic genes to specific tissues or disease sites, including areas that are otherwise challenging to reach, such as deep tumors or lesions within the central nervous system.

In one study, Alabdallah & Kotb reported the development of a bacterial drug delivery system using silver nanoparticles synthesized by Pseudomonas aeruginosa [15]. The silver nanoparticles, engineered to attach to bacterial surfaces, allowed for the sustained release of antimicrobial agents in infected tissues, enhancing treatment efficacy and reducing the dosage required. This bacterially-guided delivery is particularly valuable for hard-to-reach areas where traditional treatments struggle to penetrate. Additionally, engineered Bacillus subtilis combined with zinc oxide nanoparticles has shown potential in crossing the blood-brain barrier, offering a means of treating brain tumors and neurological disorders more effectively [20].

## Future Directions and Challenges

### Scaling Up Synthesis

While microbial nanotechnology presents promising medical applications, scaling up the production of microbial nanoparticles is essential to meet industrial demands. Currently, most microbial nanoparticle synthesis occurs at laboratory scales, which limits widespread adoption. Research must address methods for large-scale cultivation of microbial cultures and efficient recovery of nanoparticles from these systems. Sans-Serramitjana & De la Torre highlight the need for continuous culture techniques and bioreactors tailored to support microbial growth and nanoparticle production, ensuring consistency and reducing production costs [22].

### Regulatory and Safety Concerns

The introduction of microbial nanoparticles into medical applications requires careful examination of safety and regulatory standards. The long-term impact of nanoparticles, particularly those synthesized by microbes, on human health and the environment remains a concern. Although many studies confirm their efficacy, more research is needed to understand potential cytotoxicity, bioaccumulation, and long-term environmental effects of nanoparticle use [16]. Regulatory agencies must develop frameworks to standardize nanoparticle safety assessments, ensuring that these novel therapies can be safely integrated into clinical practices without unintended risks to patients or ecosystems.

Future research will likely focus on creating non-toxic, biodegradable nanoparticles to minimize potential adverse effects, while also investigating recycling methods for nanoparticles used in industrial and clinical settings. Additionally, strategies to refine microbial synthesis processes, such as genetic modification to optimize nanoparticle yield and stability, are essential to drive the adoption of microbial nanotechnology on a broader scale.


## Conclusion

When it comes to cutting-edge solutions in many different industries, such as healthcare, farming, and environmental protection, microbial nanotechnology is unrivaled. One sustainable alternative to traditional chemical synthesis is the use of microbes as "nanofactories," which allow researchers to produce nanoparticles in an environmentally benign and scalable manner. Antibiotic resistance, food insecurity, and environmental degradation are three of the most pressing global issues today; microbial nanoparticles provide novel solutions thanks to their biocompatibility and improved functioning.

In the fight against drug-resistant infections and for better targeted cancer treatments, microbial nanoparticles show great potential as a medicinal tool. By making crops more resistant to environmental stresses, these nanoparticles help farmers use less chemical fertilizers and pesticides. Microbiological nanoparticles help with bioremediation, which is good for the environment because it cleans up polluted areas and cuts down on industrial waste.

Scalability, regulatory frameworks, and safety are three areas that need further investigation before microbial nanotechnology can reach its maximum potential. The transfer of knowledge from academic labs to real-world businesses requires mass-production methods. In order to evaluate the safety of nanoparticles, regulatory bodies require thorough criteria that take into account the particles' possible toxicity and environmental effect. The integration of microbial nanotechnology into mainstream applications and the advancement toward a future that prioritizes sustainability and health depend on resolving these problems [25-38].

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