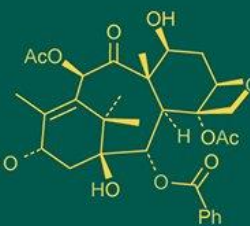
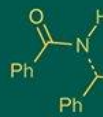


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(6): 1149-1154
www.biochemjournal.com
Received: 02-05-2026
Accepted: 03-06-2026

Jahnvi Arora
Department of Microbiology,
COBS&H, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Poonam Ranga
Department of Microbiology,
COBS&H, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Kamla Malik
Department of Microbiology,
COBS&H, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Monika Kayasth
Department of Microbiology,
COBS&H, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Sonu Chauhan
Department of Chemistry,
COBS&H, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Corresponding Author:
Poonam Ranga
Department of Microbiology,
COBS&H, CCS Haryana
Agricultural University, Hisar,
Haryana, India

Nano-bioremediation in agriculture: Emerging strategies for soil health improvement

Jahnvi Arora, Poonam Ranga, Kamla Malik, Monika Kayasth and Sonu Chauhan

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i6Sn.8779>

Abstract

Soil deterioration and agricultural pollution have become significant environmental issues resulting from improper farming methods, indiscriminate pesticide use, industrial effluents and the accumulation of harmful pollutants in agricultural ecosystems. Heavy metals, pesticide residues, hydrocarbons and other persistent pollutants negatively affect soil physicochemical properties, microbial diversity, nutrient cycling and crop productivity which threatening long-term agricultural sustainability. Conventional remediation approaches, including physicochemical and thermal methods, are often associated with high operational costs, secondary pollution and disruption of native soil microbiota. Due to these problems, nano-bioremediation gained considerable attention as an environmentally sustainable and technologically advanced strategy for restoration of contaminated agricultural soils. Nano-bioremediation is an emerging approach that utilizes the combined action of microorganisms and nanomaterials to reduce environmental pollution effectively. Microorganisms such as bacteria, fungi, algae and actinomycetes naturally participate in the decomposition of contaminants and maintenance of nutrient balance in soil ecosystems. The incorporation of nanoparticles further improves this process by enhancing pollutant adsorption, increasing catalytic reactions and improving the accessibility of contaminants for microbial degradation. Recent progress in nanobiotechnology has expanded the application of nano-bioremediation in areas including heavy metal remediation, pesticide removal, wastewater purification and restoration of soil productivity. This article examines the significance of nano-bioremediation in sustainable agriculture by discussing its working mechanisms, practical agricultural applications, environmental benefits, existing challenges and future potential in improving soil health.

Keywords: Nano-bioremediation, sustainable agriculture, soil microbiology, nanobiotechnology, heavy metal remediation

Introduction

Soil is an important and biologically active natural resource that help plants to grow and ecosystem sustainability. In addition to supporting plant growth, soil functions as a complex ecological niche inhabited by diverse microbial communities involved in breaking down organic matter, recycling nutrients, storing carbon and maintaining soil fertility (Tahat *et al.*, 2020) ^[1]. However, rapid industrialization, urban expansion and intensive agricultural practices have damaged soil quality across the world.

Modern agricultural systems uses large amounts of chemical fertilizers, pesticides and herbicides heavily to increase crop production and industrial inputs to meet increasing food demands. Excessive and continuous application of these chemicals has resulted in the accumulation of toxic pollutants in agricultural soils (Khmelevtsova *et al.*, 2022) ^[2]. In addition, industrial wastewater, mining processes, sewage waste and improper disposal of harmful materials also add toxic substances to the soil.

Heavy metals such as lead, cadmium, chromium, mercury, arsenic and nickel are some common pollutants found in contaminated soils. Unlike organic pollutants, heavy metals are non-biodegradable and persist in soil environments for extended periods, posing severe ecological and health-related risks. Heavy metals in soil can disturb its physicochemical characteristics and negatively affects beneficial soil microorganisms responsible for nitrogen fixation, phosphorus solubilization and decomposition processes (Rashid *et al.*, 2023) ^[3]. Alterations in microbial diversity and enzymatic activities ultimately leading to poor soil

fertility and lower crop yield. In addition, toxic contaminants may accumulate in edible plant tissues and subsequently enter the food chain, threatening both environmental and public health (Angon *et al.*, 2024) ^[4].

Traditional methods used to clean contaminated soil, such as soil removal, chemical treatment, heating processes and stabilization techniques are often economically expensive and environmentally invasive. These methods may further disturb native soil microbial communities and reduce biological activity essential for soil restoration. Consequently, there is an increasing demand for sustainable, cost-effective and eco-friendly remediation approaches capable of restoring contaminated agricultural ecosystems without causing additional environmental stress (Sales da Silva *et al.*, 2020) ^[5].

Bioremediation is considered an environmentally friendly method that uses microorganisms and their metabolic pathways for degradation, transformation or detoxification of environmental pollutants. In recent years, integration of nanotechnology with biological remediation processes help naturally in reducing contamination through their biological activities. Nanoparticles possess unique properties such as high surface-area-to-volume ratio, enhanced reactivity, catalytic efficiency and adsorption capacity, which help in enhancing pollutant removal (Vázquez-Núñez *et al.*, 2020) ^[6]. The combined action of nanoparticles and beneficial microorganisms has shown great potential in remediation of heavy metalcontaminated soils, degradation of pesticide residues, restoration of soil microbial activity and enhancement of plant growth under stress conditions. Due to these benefits, nanobioremediation is increasingly

recognized as an eco-friendly and sustainable approach for maintaining soil health and developing stronger agricultural systems (Hemalatha *et al.*, 2022) ^[7].

Overview of Nano-Bioremediation in Polluted Soils

Nano-bioremediation of polluted soils begins with interaction between pollutants and remediation agents present in contaminated soil. Beneficial microorganisms utilize metabolic pathways and extracellular enzymes to degrade toxic organic compounds and transform hazardous substances into less toxic forms.

Nano-bioremediation begins in contaminated soils containing heavy metals, pesticides, hydrocarbons and other pollutants (Figure 1). Following the introduction of beneficial microorganisms and nanoparticles, interactions occur that enhance pollutant bioavailability and remediation efficiency. Various mechanisms, including biosorption, bioaccumulation, biodegradation, bioleaching, enzymatic degradation and nanoparticle-assisted adsorption, contribute to pollutant removal (Singh *et al.*, 2023) ^[8]. These processes ultimately reduce contaminant toxicity and restore soil fertility, microbial diversity, nutrient cycling and plant productivity.

At the same time, nanoparticles enhance remediation efficiency due to their high surface-area-to-volume ratio, adsorption capacity, catalytic activity and reactivity. These particles can bind with heavy metals and other pollutants, making them easier to remove or degrade. Nanoparticles also increase the availability of pollutants for microbial action and speed up the degradation process (Bhandari *et al.*, 2023) ^[9].

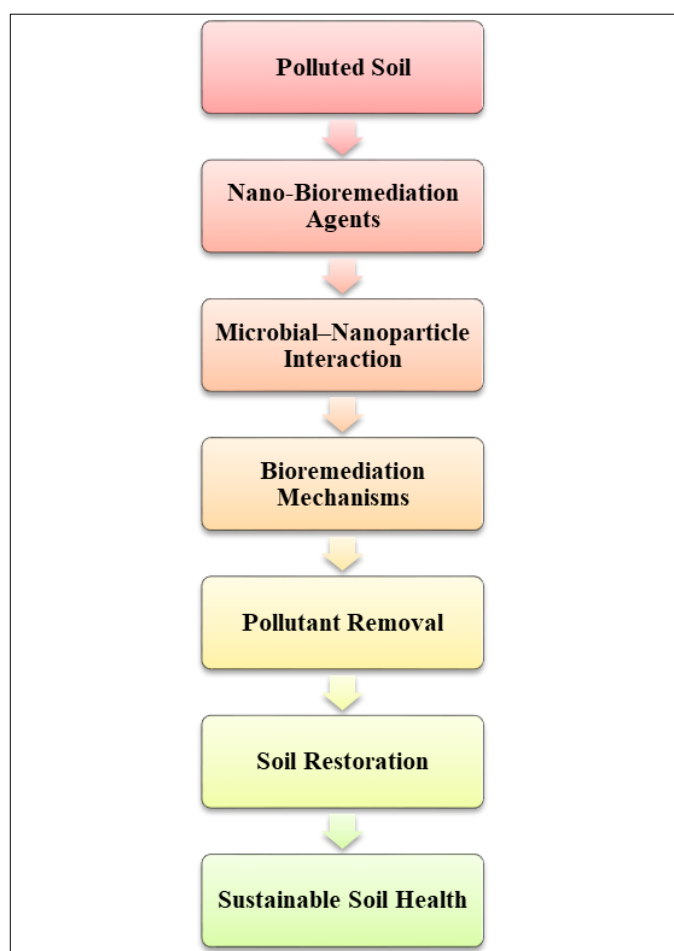


Fig 1: Schematic overview of the nano-bioremediation process for restoration of contaminated soil

Mechanisms Involved in Nano-Bioremediation for Sustainable Soil Health Improvement

One important process is biosorption, in which microbial cell surfaces bind heavy metals and other toxic substances. Functional groups present on microbial cell walls, such as carboxyl, hydroxyl, amino and phosphate groups, facilitate the adsorption of contaminants, thereby reducing their mobility and toxicity in soil (Priya *et al.*, 2022) ^[10]. Following adsorption, microorganisms can perform bioaccumulation, pollutants are taken up into microbial cells and transformed into less toxic forms. Certain bacteria and fungi can tolerate toxic substances and store them intracellularly, thereby reducing their environmental impact (Nnaji *et al.*, 2023) ^[11]. Another important mechanism is biodegradation, in which microorganisms enzymatically break down complex organic pollutants, including pesticides, hydrocarbons, dyes and industrial chemicals, into simpler and less toxic compounds through various metabolic pathways (Fouad *et al.*, 2022) ^[12]. In bioleaching, microorganisms produce organic acids and chelating agents

that solubilize heavy metals from contaminated soils, facilitating their subsequent removal from the environment (Adetunji *et al.*, 2023) ^[13]. Microbial enzymes also contribute through enzymatic degradation. Enzymes such as laccases, peroxidases, oxidoreductases and hydrolases catalyse the breakdown of harmful pollutants into simpler and less toxic products, thereby supporting detoxification and improving soil quality (Adetunji *et al.*, 2021). In addition, nanoparticles contribute through nanoparticle-assisted adsorption. Owing to their high surface area and reactivity, nanoparticles effectively adsorb and immobilize pollutants, enhancing overall remediation efficiency. Finally, the combined activity of microorganisms and nanoparticles creates a strong synergistic interaction that enhances pollutant degradation, nutrient availability, microbial diversity and plant growth (Narayanan *et al.*, 2023) ^[15]. Consequently, nano-bioremediation restores soil fertility, reduces environmental toxicity and promotes sustainable agricultural productivity. The major remediation mechanisms and their outcomes are illustrated in Figure 2.

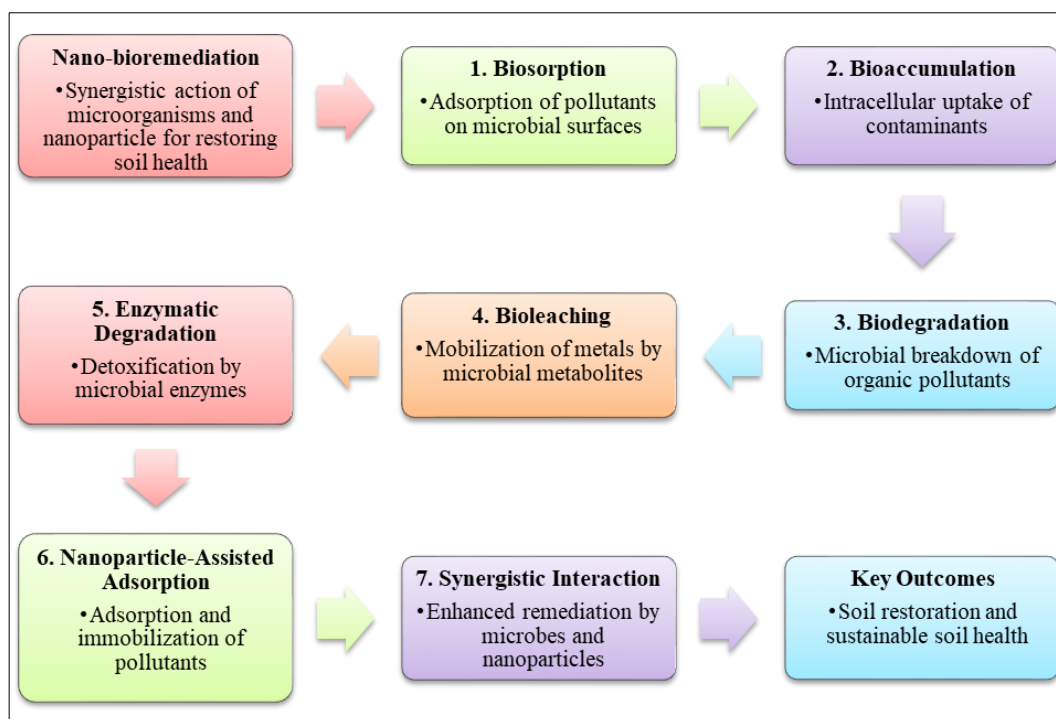


Fig 2: Mechanisms and Outcomes of Nano-Bioremediation in Soil Restoration

Microorganism-Assisted Nano-Bioremediation

Microorganism-assisted nano-bioremediation is considered a sustainable and eco-friendly approach for remediation of contaminated environments. In this strategy, microorganisms are utilized for biological synthesis of nanoparticles, thereby reducing dependence on toxic chemical methods. Biologically synthesized nanoparticles exhibit improved stability, reduced environmental toxicity and enhanced remediation efficiency. Examples of Microorganism-Assisted Nano-Bioremediation illustrated in table 1.

Microbial enzymes and bioactive compounds act as reducing and stabilizing agents during nanoparticle synthesis. Fungal species such as *Aspergillus tubingensis* have been reported to biosynthesize iron oxide nanoparticles capable of efficient removal of heavy metals including

nickel, copper, lead and zinc from contaminated wastewater (Mahanty *et al.*, 2020) ^[16]. Similarly, exopolysaccharide-coated nanoparticles produced using microalgae such as *Chlorella vulgaris* have demonstrated significant adsorption capacities for ammonium and phosphate ions (Govarthanan *et al.*, 2020) ^[17].

Bacteria-mediated nanoparticle synthesis also represents a capable approach for degradation of industrial pollutants. Copper nanoparticles synthesized using copper-resistant bacterial strains have shown efficient degradation of textile dyes and industrial effluents (Noman *et al.*, 2020) ^[18].

The integration of microbial processes with nanotechnology enhances pollutant removal efficiency, minimizes secondary pollution and supports development of sustainable remediation technologies for environmental restoration.

Table 1: Examples of Microorganism-Assisted Nano-Bioremediation

Microorganism	Nanoparticle Produced	Pollutant Removed	Major Outcome	Reference
<i>Aspergillus tubingensis</i>	Iron oxide nanoparticles	Heavy metals (Ni, Cu, Pb, Zn)	Efficient removal of heavy metals from wastewater	Mahanty <i>et al.</i> , (2020) ^[16]
<i>Chlorella vulgaris</i>	EPS-coated iron oxide nanoparticles	Ammonium and phosphate ions	Enhanced adsorption efficiency	Govarthanan <i>et al.</i> (2020) ^[17]
<i>Escherichia</i> sp.	Copper nanoparticles	Textile dyes	Efficient degradation of industrial dyes	Noman <i>et al.</i> (2020) ^[18]

Applications of Nano-Bioremediation in Agriculture

Nano-bioremediation has emerged as a promising strategy for the restoration and management of polluted agricultural ecosystems. The integration of nanotechnology with microbial remediation processes improves pollutant degradation efficiency, improves soil fertility and supports sustainable agricultural productivity. Various applications of nano-bioremediation are being widely explored for treatment of heavy metal-contaminated soils, pesticide degradation, wastewater management and improvement of plant-microbe interactions. Table 2 illustrates Major Applications of Nano-Bioremediation in Agriculture.

Heavy Metal Remediation in Agricultural Soils

Heavy metal contamination is one of the most serious environmental problems affecting agricultural productivity and soil health. Toxic metals such as lead, cadmium, chromium, arsenic and mercury remain in soils for long periods and negatively influence microbial diversity, nutrient availability and plant growth (Wan *et al.*, 2024) ^[19]. Nano-bioremediation approaches utilize metal-resistant microorganisms along with nanoparticles for adsorption, immobilization, transformation and detoxification of heavy metals. Iron oxide nanoparticles, titanium dioxide nanoparticles and biochar-based nanocomposites show high adsorption capacities for toxic metals, thereby reducing their bioavailability in soil systems. Microorganisms such as *Pseudomonas*, *Bacillus*, *Aspergillus* and *Rhizobium* species play an important role in biosorption and transformation of heavy metal into less toxic forms (Medfu Tarekegn *et al.*, 2020) ^[20]. The combined action of nanoparticles and microbial communities improves remediation efficiency while minimizing environmental toxicity.

Degradation of Pesticides and Agrochemicals

Overuse of pesticides, herbicides and fungicides in modern agriculture has resulted in accumulation of persistent organic pollutants in soils. These compounds harmfully affect soil microbial communities, reduce biodiversity and contaminate groundwater resources (Jalal & Bondarenko, 2025) ^[21]. Nano-bioremediation enables degradation of pesticide residues through microbial enzymatic activity supported by nanoparticle-mediated catalytic reactions.

Microorganisms produce enzymes such as laccases, hydrolases, oxidoreductases and peroxidases that degrade toxic organic compounds into less harmful intermediates. Nanoparticles improve pollutant degradation by increasing surface interaction and catalytic efficiency. Zinc oxide and titanium dioxide nanoparticles have shown significant potential in photocatalytic degradation of pesticide contaminants under environmental conditions (Guerrero Ramírez *et al.*, 2023) ^[22].

Wastewater Treatment and Irrigation Management

Agricultural irrigation using untreated industrial and municipal wastewater introduces toxic contaminants into soil ecosystems. Nano-bioremediation technologies are increasingly being utilized for purification of wastewater prior to agricultural application (Malik *et al.*, 2022) ^[23]. In this process, Nanoparticles along with microbial biofilms help in removing heavy metals, dyes, hydrocarbons and organic pollutants from wastewater systems. Iron oxide nanoparticles and activated carbon nanocomposites have strong adsorption abilities for toxic ions, whereas microbial consortia facilitate biodegradation of organic contaminants (Mohapatra *et al.*, 2020) ^[24]. Application of treated wastewater in agriculture not only conserves freshwater resources but also reduces environmental pollution and improves sustainability of agricultural practices.

Restoration of Soil Microbial Diversity and Fertility

Soil microorganisms play important role in nutrient cycling organic matter decomposition and maintenance of soil fertility. Pollutants such as heavy metals and pesticides can decrease microbial activity and reduce soil biological quality (Alengebawy *et al.*, 2021) ^[25]. Nanobioremediation helps in restoration of beneficial microbial communities by reducing toxicity and enhancement of nutrient availability. Plant growth-promoting rhizobacteria combined with nanoparticles improve soil enzyme activity, root development and nutrient uptake efficiency in plants (Verma *et al.*, 2024) ^[26]. Biochar nanoparticles and nano-fertilizers also contribute to improved soil aeration, moisture retention and microbial colonization, thereby supporting longterm soil fertility restoration (Abbas *et al.*, 2025) ^[27].

Table 2: Major Applications of Nano-Bioremediation in Agriculture

Application Area	Role of Nano-Bioremediation	Major Outcomes	References
Heavy metal remediation	Adsorption and detoxification of toxic metals	Reduced soil toxicity and improved crop growth	Abd Elnabi <i>et al.</i> , 2023 ^[28]
Pesticide degradation	Microbial degradation of agrochemical residues	Reduced environmental pollution	Tazeen <i>et al.</i> , 2025 ^[29]
Wastewater treatment	Removal of pollutants from irrigation water	Safer agricultural irrigation practices	Thangavelu and Veeraragavan, 2022 ^[30]
Soil fertility restoration	Enhancement of microbial activity and nutrient cycling	Improved soil health and productivity	Goud <i>et al.</i> , 2022 ^[31]
Phytoremediation support	Enhancement of plant tolerance under stress conditions	Increased remediation efficiency	Gomes, 2025 ^[32]

Outcomes and Environmental Significance

Nano-bioremediation provides many environmental and agricultural benefits compared to traditional remediation technologies. The synergistic interaction between microorganisms and nanoparticles improves remediation efficiency while maintaining ecological sustainability.

one major benefits of nano-bioremediation is reduction in heavy metal bioavailability within agricultural soils which minimizes toxic effects on crops and soil microorganisms. Restoration of microbial diversity enhances nutrient cycling and increases the biological activity of soil.

This approach further supports higher agricultural productivity through improved soil fertility, improved plant growth and reduced pollutant accumulation in crops. Furthermore, this approach supports sustainable agriculture by minimizing chemical usage and reducing secondary pollution.

Nano-remediation supports circular bioeconomy and green environmental management by promoting eco-friendly remediation strategies and conservation of natural resources.

Challenges and Limitations

Nano-remediation has shown great potential still faces several scientific, environmental and economic challenges that limit its large-scale agricultural applications. One of the major concern associated with nano-bioremediation is nanoparticle toxicity. Certain engineered nanoparticles show toxic effects on beneficial soil microorganisms, plants and non-target organisms at elevated concentrations. Long-term environmental fate and accumulation of nanoparticles in soil ecosystems are still not fully understood. Another major challenge is the high cost production of nanoparticle, stabilization and large-scale field implementation. Most nano-bioremediation studies are currently limited to laboratory-scale experiments and limited information is available regarding field-level performance under variable environmental conditions. Environmental factors such as soil pH, temperature, moisture content and pollutant concentration significantly influence microbial activity and remediation efficiency. Maintaining microbial survival and functionality under highly contaminated conditions remains difficult. Additionally, lack of standardized protocols, regulatory frameworks and public awareness further restricts commercialization and practical adoption of nanobioremediation technologies in agricultural sectors.

Future Perspectives

Future research in nano-bioremediation should focus on development of environmentally safe and biodegradable nanomaterials that do not create harmful effects on the environment. Research in genetic engineering and synthetic biology approaches may also helps in improving microbial tolerance and pollutant degradation efficiency. Integration of nano-bioremediation with phytoremediation, biofertilizers, precision agriculture and smart monitoring systems can further improve soil restoration methods. Continuous progress in nanobiotechnology and environmental microbiology are expected to support the development of sustainable agricultural systems capable of maintaining long-term soil health and environmental resilience.

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