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Microbial Nanotechnology for Sustainable Future

Industrial and Environmental Perspectives

Edited by Yugal Kishore Mohanta, Bishwambhar Mishra, and Tamanna Bhuyan

Microbial Nanotechnology for Sustainable Future

This book covers the fundamentals and methods of biologically producing nanoparticles using microorganisms such as bacteria, fungi, and algae, along with optimization strategies for microbe-mediated nanoparticle production. It explores industrial and agricultural applications of microbial nanoparticles and their use in healthcare and pharmaceuticals, including treatments for multidrug-resistant infections and cancer. Focusing on microbial nanotechnology, this book highlights its applications in food production, pharmaceuticals production, water treatment, and environmental remediation. It provides valuable insights for researchers and students into food sciences, biotechnology, microbiology, and pharmaceuticals. Additionally, it discusses the environmental applications of microbial nanotechnology, emphasizing recent advancements and future research directions, serving for both academic and industrial researchers as a guide to transformative applications in this field.

Features

- Gives an overview of microbial nanotechnology and its applications to the environment
- Deals with the challenging effects of microbial nanotechnology on the environment, human health, safety, and sustainability
- Offers guidelines and cutting-edge methods and trends for environmental remediation
- Examines how nanotechnology can facilitate the detection of minute amounts of viruses, bacteria, and other pollutants in food and other industrial applications
- Incorporates case studies and real-world applications to show how microbial nanotechnology affects contemporary sciences and technologies

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Designed cover image: Getty

First edition published 2026
by CRC Press
2385 NW Executive Center Drive, Suite 320, Boca Raton FL 33431

and by CRC Press
4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

CRC Press is an imprint of Taylor & Francis Group, LLC

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ISBN: 978-1-032-78242-3 (hbk)
ISBN: 978-1-032-78276-8 (pbk)
ISBN: 978-1-003-48714-2 (ebk)

DOI: 10.1201/9781003487142

Typeset in Times
by codeMantra

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13 Bioremediation of Various Industrial Effluents Utilizing Microorganism-Assisted Nanotechnology

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DOI: 10.1201/9781003487142-13

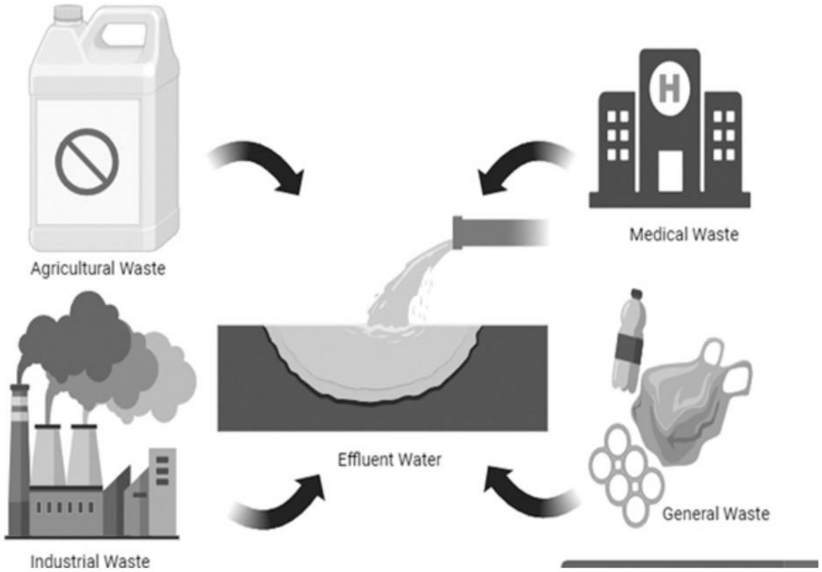
13.1 INTRODUCTION

One of the biggest global concerns is how to handle industrial sludge in a way that is both environmentally and economically feasible. The methods used for disposing industrial sludge includes burning, composting, drying at high temperature, dispersing the sludge on the ground, lime stabilization, and landfilling. The bulk of India's textile industry discharges its waste into agriculture fields, waste yard, fallow ground, poorly managed wasteland, and along railroad line due to exorbitant sludge management costs, which further contaminates groundwater, creating a serious threat to human health. Meanwhile, landfilling and waste disposal have become increasingly expensive and impractical due to limited available landfill space, stringent national waste disposal regulations, and heightened local awareness. In the majority of developing nations, sludge management procedures are inadequate and not well developed. Nowadays, several factories are practicing ecofriendly and low-cost industrial effluent treatment processes [1]. The improper handling and subsequent discharge of dangerous effluents into groundwater and other large water bodies through sewage drains adversely affect animal health and aquatic life. Additionally, inadequately treated effluents may lead to contamination of air, land surface, soil, and other elements of the ecosystem [2].

Because of inadequate wastewater treatment facilities, including proper electric power supply, inadequate sustenance, and shortage of skilled and experienced labour, industrial effluents are very often discharged into water bodies, which has negative impact on underwater life. Contamination of groundwater and other water sources can harm both human health and the ecosystem [3]. In order to meet the growing demand for metals, society has been forced to increase mining operations, largely due to the overuse of natural resources. Consequently, expansion of industries results in increased resource and water consumption, which leads to the release of a significant amount of heavy metals as effluents. As a result, industrial wastewater management has gained international attention. Several research studies and experiments have been carried out to recycle wastewater and utilize it for various processes [4]. Nevertheless, each of these techniques still has some imperfections such as low productivity, the enormous amounts of solvents and reagents required, and the production of secondary pollutants such as dangerous chemicals, sludge, waste residues, and effluents [5]. Therefore, it is now essential everywhere to find affordable, environmentally friendly ways to treat wastewater more effectively. The objective of this study is to give a clear view to researchers and industry stakeholders about the present scenario, available treatments, difficulties, and possibilities related to wastewater treatment techniques. This study additionally uncovers feasible methods for treating wastewater and turning it into readily available and highly valuable supplies of clean water, all of which help to fulfil sustainable development goals.

13.2 IMPACT OF INDUSTRIAL EFFLUENT

A country's economic progress is increasingly dependent on rapid industrialization and urbanization, which are also essential for human welfare. However, it is also turning into a growing source of water pollution and a potent, unavoidable danger to upset the environment's balance and ecosystem. Numerous hazardous industrial pollutants have either directly or indirectly poisoned various biological forms after being poorly processed and released into water sources. Heavy metals are one of the nature's primary, persistent, and non-biodegradable water pollutants. Certain dangerous heavy metals that aquatic animals ingest can harm the health of other species and ultimately humans through the food chain. They may result in diminished growth and development, oxidative stress, organ damage, nervous system abnormalities, and cancer. The tannery effluent ranked highest among all the industrial wastes [6]. The various sources of industrial effluent are listed in Figure 13.1.



▶ Long Description for Figure 13.1

FIGURE 13.1 Various sources of effluent water. ↩

Phenolic compounds are another common chemical contaminants released by industry. They affect the processes of biological treatment by preventing normal microbial activity, which is how they demonstrate toxicity. Additionally, they may result in cyanosis, sweating, low body temperature, reflex loss, reduced breathing, and respiratory failure. Genotoxicity and mutagenicity can be caused by the main effluent elements of the paper and pulp industries, such as tannins, resins, and chlorinated organic compounds. In addition, they can result in a decrease in reflexes, perspiration, lowered body temperature, cyanosis, and difficulty breathing. The tannins, resins, and chlorinated organic compounds from the pulp and paper industries can cause genotoxicity and mutagenicity. Lignin is an important industrial waste from the pulp industry. During biological treatment, they may transform into hazardous chemicals and are partially biodegradable.

This, in turn, affects the hormonal balance of aquatic animals. Certain essential sterols, such stigmasterol and β-sitosterol, can bind to fish oestrogen receptors and cause reproductive disorders. Chromium compounds and oil foam form a colloidal substance that hinders sunlight from entering water bodies and reduces the amount of dissolved oxygen. Many textile industries use organic dyes related to chlorine, which are carcinogenic. The tannery and textile effluents can increase the level of Chemical Oxygen Demand and Biochemical Oxygen Demand. Sodium and chromium adversely affect the plant growth, soil quality and water bodies. For a clean and healthy environment, it is crucial to use efficient methods to eliminate these harmful contaminants before they reach different water bodies. The effects of industrial effluents are shown in Figure 13.2.

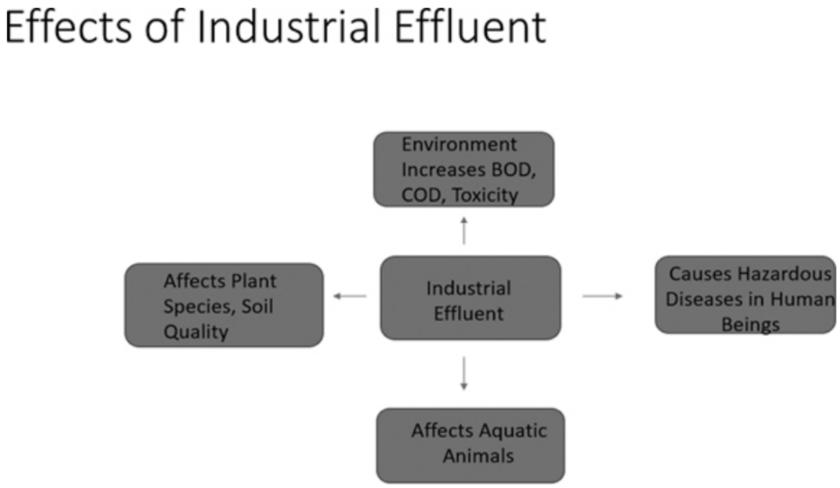


FIGURE 13.2 Effects of industrial effluents. ⏎

13.3 METHODS OF TREATING INDUSTRIAL EFFLUENTS

The primary industries that contribute to the presence of metals in wastewater include chemical, petrochemical, sugar, textile and dyeing, bleaching, paper and pulp, mining and quarries, organic chemical, nuclear power, leather/tannery, iron and steel, electric power plants, metal refining, soap and detergent, pharmaceutical, pesticide and biocide metal processing, and electroplating industries [7].

The advancement of technology and research has improved the research ideas to extract valuable raw materials from industrial effluents. In order to lessen their harmful effect on human health and preserve the aesthetic value of the environment, many techniques have been developed. The industrial effluent water was treated using chemical, biological, and physical processes. Several advances and breakthroughs in hybrid technology, which combines two and more processes, have increased the recovery rate and efficacy [8]. The various effluent treatment processes are listed in Figure 13.3.

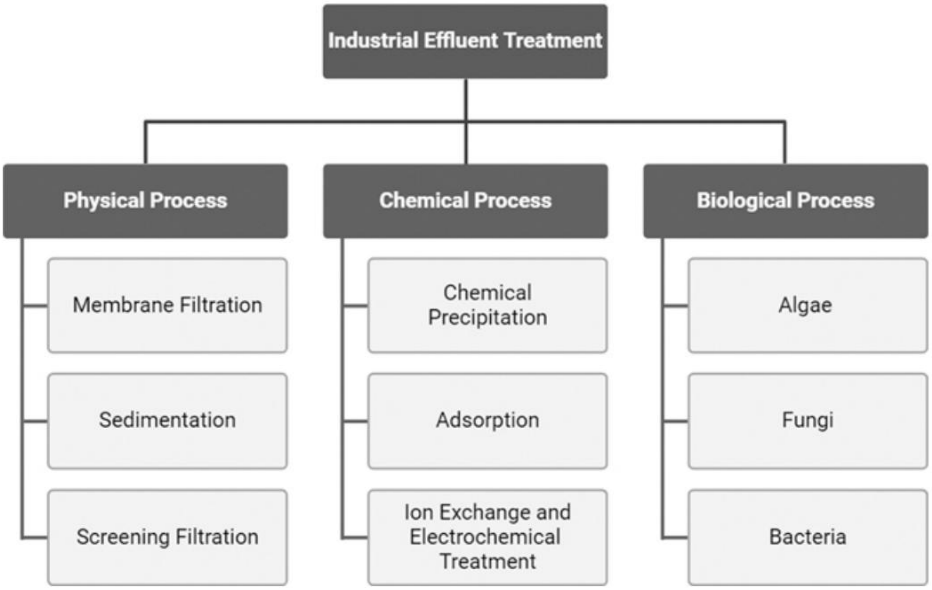


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FIGURE 13.3 Methods of industrial effluent treatment. ⏎

Most commonly, the untreated industrial wastewater effluents are discharged into water bodies, damaging normal underwater life, due to poor wastewater treatment facilities, including malfunctioning of electricity, poor sustenance, and a shortage of skilled and experienced labour. Water bodies, including groundwater, become polluted, leading to both environmental degradation and health risks [9]. A great deal of research has been carried out by utilizing biological, chemical, and physical processes. There have also been several advancements and innovations in hybrid techniques, which combine two or three methods to increase accuracy and recovery rates.

13.3.1 PHYSICAL PROCESSES

This is the first step in the treatment process to remove bigger or more solid and stable particles from the industrial wastewater. This procedure consists of membrane filtration, sedimentation, filtration, and screening [10].

13.3.1.1 Membrane Filtration

The technique of removing metal from mixed metal wastes by filtering via a porous or non-porous membrane is called membrane filtration. In simple terms, a membrane is a barrier that divides two phases apart by limiting the selective passage of constituents across it. The wastewater composition, the size of the membrane pore, and the material utilized are some of the variables that might impact the membrane's performance. This technique includes nanofiltration (NF), reverse osmosis (RO), microfiltration (MF), and ultrafiltration (UF). There is considerable similarity between UF and MF. The primary function of MF is pre-treatment, and it functions well at low pressures. The suspended or colloidal particles are separated from wastewater. Typically, the surface coating has a thickness of 10–150 µm. This membrane removes oil, grease, particles, germs, and organic materials [10,11]. Track-etching, phase inversion, stretching, and sintering are the processes used to produce the membranes for MF methods. The surface layer thickness in UF is typically 150–250 µm. Proteins, viruses, polysaccharides, and macromolecules are eliminated using this membrane. It is more efficient and uses less energy. High pressure is necessary to flow water through NF, which effectively separates substances with low molecular weights at a pore size of 0.001 µm. Typically, the surface coating has a thickness of 150 µm. High molecular weight substances, like mono-, di-, and oligosaccharides, are removed by this membrane. NF is capable of efficiently removing heavy metals from industrial effluents [10]. RO is frequently used with a semi-permeable membrane to extract salt from salty water. It is capable of successfully eliminating the multivalent ions from industrial wastewater. The surface coating typically has a thickness of 150 µm. Amino acids, glucose, proteins, sodium chloride, and high- and low-molecular-weight substances are all eliminated using this membrane [10].

13.3.1.2 Sedimentation

Sedimentation is the process of making the suspended solid particles in wastewater to settle down. Wastewater treatment facilities employ sedimentation basins to separate water from suspended particles. Secondary clarifiers are employed in biological processes, such as the activated sludge process, to eliminate settleable particles that are produced as an active component of the biological process. To accelerate the process, chemicals can be added externally to the aqueous media. The flow speed, detention duration, and solid loading can all have a significant impact on sedimentation efficiency [12,13].

13.3.1.3 Screening and Filtration

In this process, the suspended or floating items are removed from the wastewater. Screens of different sizes are used for different particles. To remove oils, grease, germs, and other materials through filtering, pore sizes between 0.1 and 0.5 mm are utilized [12].

13.3.2 CHEMICAL PROCESSES

13.3.2.1 Chemical Precipitation

One popular conventional method for removing metals from wastewater is chemical precipitation, which involves adding various chemicals. Chemical precipitation falls into several types, including hydroxide precipitation, chelating precipitation, and sulphide precipitation. The pH shift is the crucial factor in the process [14]. However, during the precipitation process, sludge gets produced in large quantities, which raises the expense of management and disposal [14]. The concentration of wastewater, the quantity of metals in the wastewater, the reaction's parameters, and the presence of substances that might inhibit reactions all have an impact on the efficiency of the process.

13.3.2.2 Adsorption

The conventional technique for extracting metals from wastewater is adsorption. This method works well and offers a lot of surface area for the metals to be adsorbed. This technique involves the passing of metal-containing wastewater through a solid phase that is called as an adsorbent. On the surface, the specific metals that are adsorbed may then be gathered and separated. After the removal of metal from the adsorbent, desorption method was used to replenish it. Natural materials, industrial by-products, and agricultural waste can all be sources of the adsorbent. The most frequently used adsorbent is activated carbon. Other adsorbents are sawdust, fly ash, rice husk, carbon nanotubes, zeolite, water hyacinth, orange peel pith, coconut coir pith, sunflower, etc. The selectivity of the adsorbents influences the cost of activated carbon throughout the adsorption process. Certain adsorbents are mechanically weak, have poor adsorption capacity, and may disintegrate in acidic environments. This procedure involves choosing the right adsorbent and waste products produced, which requires more consideration [15].

13.3.2.3 Ion Exchange Treatment

Ion exchange is the process of exchanging ions between the liquid and solid phases. The exchanging of ions is influenced by a number of factors such as temperature, pH, anions, adsorbent concentrations, initial sorbate, and contact duration. Typically, metals from wastewater are removed using natural or synthetic resins. Metals from wastewater are often removed using synthetic or natural polymers. Unfortunately, there are several drawbacks with this method. For example, it is not that much cost-effective because the resins required are very sensitive to the particles being removed and expensive, which results in reduced efficiency of metal extraction. Additionally, it is necessary to change the resins periodically because repurposed resins eventually begin to deteriorate and smell nasty [14]. The ion exchange wastewater treatment was illustrated in Figure 13.4.

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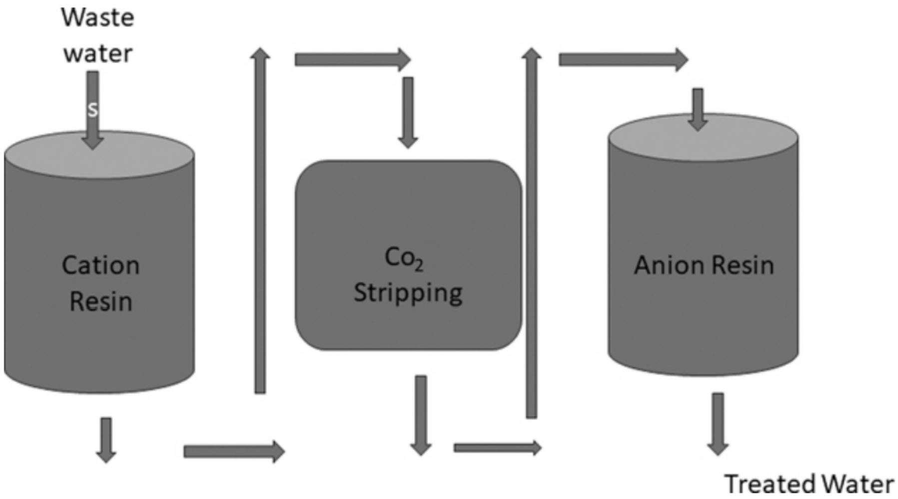


▶ Long Description for Figure 13.4

FIGURE 13.4 Ion exchange wastewater treatment. ⏎

13.3.2.4 Electrochemical Treatment

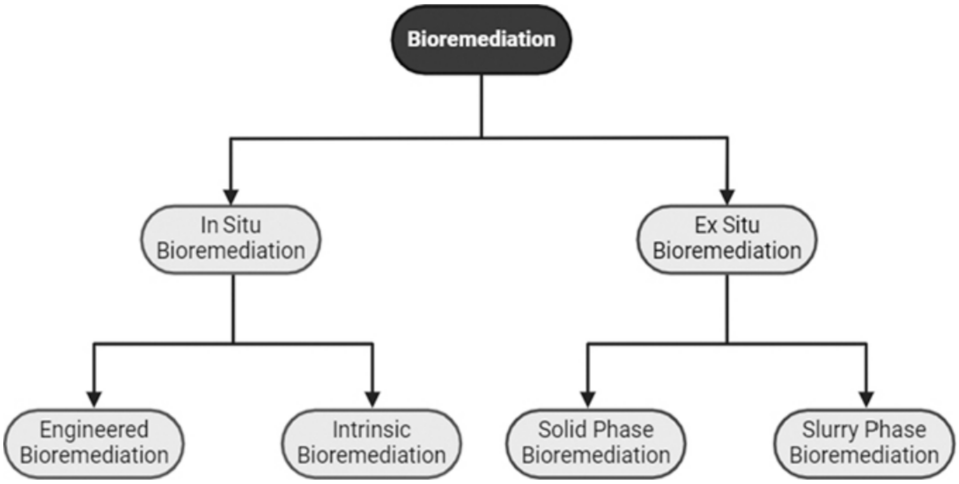
It is possible to clean municipal and industrial wastewater using electrochemical technologies. Preliminary removal of bigger particles and other physical inclusions from water is accomplished by conventional treatment. Once this requirement exists, any type of pollution, including ions, bacteria, and organic and inorganic components, may be eliminated using electrochemical techniques, producing pure water with distilled water quality. The most popular electrochemical water treatment techniques are electrochemical reduction, which recovers metals and changes persistent organic compounds into less toxic forms; electrocoagulation and electro flotation, which remove suspended particles; electrodialysis; and electrochemical oxidation, which mineralizes organic pollutants, disinfects water, and removes cyanides and sulphides. Electrodialysis is also used to desalinate water, while electroflotation is used to remove suspended particles [16].

13.3.3 Biological Process

The alternative process to conventional metal recovery procedure is the biological process. Microorganisms are crucial to the biological treatment of wastewater. Bacteria are used to break down metallic compounds into simpler forms so that they may be more easily separated from mixed metal solutions [17].

13.4 BIOREMEDIATION

Bioremediation is a prominent and inventive technology because of its eco-friendliness and economic expediency. In such technology, the naturally growing microbial strains degrade toxic substances into nontoxic ones. This degradation is mainly done by enzymes. Hazardous materials can be broken down or detoxified by the use of bioremediation, which involves giving the organisms the nutrition and other elements they require to thrive. Every phase of the metabolic process depends on enzymes [18]. It belongs to a family that also includes hydrolases, lyases, transferases, and oxidoreductases. Numerous enzymes may break down a broad variety of substrates due to their specific and non-specific substrate affinities. The effectiveness of bioremediation depends on the contaminants' enzymatic activity. During bioremediation, it is frequently necessary to adjust ambient factors in order to hasten microbial growth and breakdown [19]. The most commonly used methods of bioremediation are listed in Figure 13.5.



▶ Long Description for Figure 13.5

FIGURE 13.5 Types of bioremediations. ↩

13.5 ADVANTAGES OF BIOREMEDIATION

Environmental pollutants can be effectively and economically removed by the process of bioremediation [20]. Promoting plant growth, controlling insects, protecting soil, recycling nutrients, and lowering pollutants are some of the crucial roles played by soil microorganisms [21]. Bioremediation had become more significant because of its cost-effectiveness, societal acceptability, and efficiency. Bacteria play a key role in bioremediation. Archaea have been identified to have a role in bioremediation in a variety of bacterial-based applications. Microbes can also aid in the removal of impurities from industrial waste that is basic, acidic, hypersaline, or hyperthermal [22]. Based on current research studies, employing many live organisms in bioremediation can lead to better outcomes and efficiency, as well as more microbial diversity. The bioremediation technique was utilized by several researchers to eliminate the inorganic and organic contaminants [23,24]. In a research study, *Aspergillus sydowii* was used to treat a variety of contaminants using bioremediation technology, including endophytic fungus and organophosphate pesticides including profenofos, methyl parathion, and chlorpyrifos [25].

Microbial enzymes are employed in the bioremediation process in order to convert hydrocarbons into less harmful substances. The widespread application of genetically modified microorganisms that may also help to remove xenobiotic substances, including petroleum, naphthalene, toluene, and benzene, is currently being investigated [24]. The ambient temperature, aerobic or anaerobic conditions, and nutrient availability are some of the factors that influence bioremediation for improved outcomes. Emerging environmental pollutants, which are mostly brought into ecosystems by human activity, include poisons, heavy metals, persistent organic compounds, and air pollutants that can be either natural or artificial. These pollutants represent a hazard to all living things, including humans, animals, and plants. One of the most economical and environmentally advantageous biotechnological developments is bioremediation. Waste management is mainly based on bioremediation. Because of their difficulty in breaking down, persistent organic pollutants are considered as heterologous biological substances [26].

13.6 ROLE OF NANOTECHNOLOGY IN WASTEWATER TREATMENT

A robust economy and the development of society mainly depend on access to safe and clean water, which is a basic human necessity. There are steps being taken to lessen the current circumstances. The ecology is adversely affected by wastewater produced from both industrial and residential sources [27]. Generally, chemicals are used to tackle this problem, which may contribute to the rising concern over wastewater treatment. The treatment process needs to be easy, economical, and ecologically benign. It has been proven that nanomaterials may effectively remove a variety of contaminants from wastewater [28]. Nanotechnology has developed into a viable and environmentally beneficial method for treating water and other environmental clean-ups in recent years. Toxic contaminants have been effectively adsorbed, degraded, and removed from water bodies by means of this technology through the structural and physiochemical alteration of frequently used materials [29].

The efficacy of water treatment systems has been increased by a variety of engineered nanomaterials and tools that have been created at the molecular and atomic level, including photocatalysis, dendrimers, biosorption, and nano-filters [30].

In addition, various kinds of integrated and composite treatment filters or system, such as those made of mixed oxides, zeolites, metallic and bimetallic nanoparticles, and carbon nanotubes and wires, are made of chemical and biogenic nanoparticles (NPs) and are intended to improve the surface-volume ratio, have better reaction, and neutralize the toxins with a notable recovery rate [31]. In nanotechnology, the use of nanomembranes to remove physical particles and molecules, as well as biological and chemical pollutants, softens water. Consequently, the field of nanobiotechnology has broadened to encompass the production and entrapment of nanoparticles (NPs) for bioremediation using microbes and their active catalytic molecules as bio-nanomachinery.

Microorganisms and their enzymes are used for removing the hazardous pollutants in wastewater by the process of bioremediation. Microbially assisted nanotechnology is economical and environmentally beneficial [32]. Hazardous dyes, pharmaceuticals, and other developing toxins emitted by industry, municipal, and agriculture waste in water bodies is efficiently broken down and removed by the nanoparticles generated by bacteria or biogenic nanoparticles. These nanoparticles are not only used to remove chemical and heavy metal contaminants from wastewater, but they also show promise in terms of detecting pathogens, toxicants, and disinfection by-products using sensing technologies [33]. Some of the nanotechniques currently used for wastewater treatment are listed in Table 13.1.

TABLE 13.1
Current Nanotechniques Used for Wastewater Treatment ⏎

S. No.	Nanotechnique Methods for Wastewater Treatment	Nanomaterials Involved	Description
1	Adsorption	Carbon-based nanotubes, carbon-based nanoadsorbents, and nano metal oxide are used	Through absorption, wastewater is cleaned by removing organic and Inorganic substances from it [30].
2	Membrane and membrane process	Nano-TiO_2 nano-Ag, nanozeolites	This method efficiently purifies wastewater with less usage of chemicals [31].
3	Photocatalysis	Fullerene derivatives, TiO_2 photocatalyst	Photocatalysis process eliminates hazardous pollutant and microorganisms [30].
4	Sensing and monitoring	Quantum dots, CNTs, and nanoparticles	These nanosensors detect pathogens and remaining residues in water [31].
5	Microbial-assisted nanotechnology	Example: *Pseudomonas aeruginosa* synthesizes zirconia nanoparticles which was involved in bioremediation [34]	The microbial-assisted nanotechnology is ecofriendly and cost-effective [32]. Pharmaceuticals, toxic dyes, and other emerging toxins released by municipal, agricultural, and industrial wastes into water bodies are efficiently broken down and removed by the nanoparticles generated by bacteria or biogenic nanoparticles.

13.6.1 SIGNIFICANCE OF NANO-BIOREMEDIATION

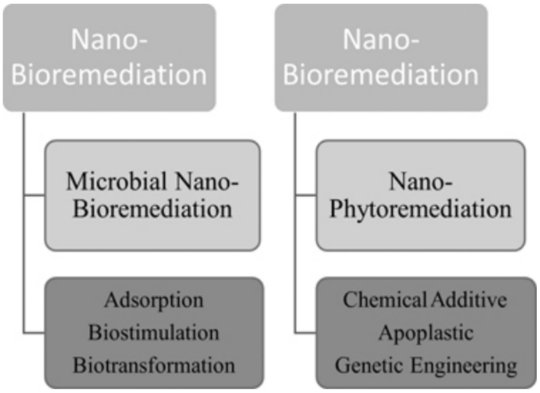
Nanotechnology has become a promising and useful technology that offers several important advantages for enhancing environmental technologies that use nanomaterials with effective performance in the bioremediation process [35]. Nano-bioremediation uses nanoparticles to speed up bioremediation, with the goal of cleansing the environment [36]. There are two subgroups under nano-bioremediation: microbial nano-remediation and nano-phytoremediation of nanoparticle [37,38].

The utilization of microorganisms to remediate contaminants is known as bioremediation. After nanotechnology and bioremediation were combined, the way nanoparticles interact with live organisms largely determines the effectiveness of nano-bioremediation. A small number of instances where biotic components and nanoparticles interacted produced biocidal effects that were shown to be detrimental to the organisms engaged in the bioremediation process [39]. Therefore, evaluating the interaction between nanoparticles and biotic components is a prerequisite for the nano-bioremediation process. The success of nano-bioremediation can be influenced by a number of variables, including the size, shape, and chemical makeup of nanoparticles, the physiological traits of the organism, the pH and temperature of the soil, and the kind of pollution [40]. These elements operate both directly and indirectly. The ideal growth of biological organisms depends on factors such as temperature, pH, and medium, and the interaction of nanoparticles with organisms controls a range of processes, including absorption, dissolution, and biotransformation. The procedure of nano-bioremediation involves two steps. First, pollutants are broken down by nanoparticles to a level that is suitable for bioremediation. Next, pollutants undergo biodegradation [41].

13.6.2 MICROORGANISMS-ASSISTED NANOTECHNOLOGY

The employment of nanomaterials and microorganisms in tandem makes nanotechnology eco-friendlier and sustainable. The chemically produced nanoparticles may have certain disadvantages in terms of self-agglomeration and chemical consumption. Thus, the green production of nanoparticles employing enzymes from plant extracts and bacterial and fungal extracts was used as an alternative. They act as reductive agents for the metal complex salt and synthesize metallic nanoparticles [42].

This microbial nanotechnology uses soil bacteria and nanoparticles to speed up the biodegradation process. The microorganisms take up metal ions, undergo a reduction process, and synthesize nanoparticles. Metals and microbial enzymes together help in the formation of nanoparticles for nano-bioremediation [43]. Microbial-assisted nanotechnology is a two-phase process [44]. In the initial stage, nanoparticles are introduced into the system, and the contaminant particles endure processes such as absorption adsorption, photocatalysis, and dissolution. In the second phase, a variety of biotic processes, such as biostimulation and biotransformation, remove these particles from the system [45]. The biotic phase, which is the second stage, is the important phase for the bioremediation of contaminants. The pollutants, including both organic and inorganic, have been treated via microbial nano-bioremediation [46]. By adding protein-based bioactive components, these nanosized particles achieve solidity in a liquid solution by co-precipitation [42]. Figure 13.6 briefly describes the methods of bioremediation.



▶ Long Description for Figure 13.6

FIGURE 13.6 Nano-bioremediation.

13.6.3 Nanotechnology Methods Combined with Microbial Assistance to Facilitate Bioremediation of Wastewater

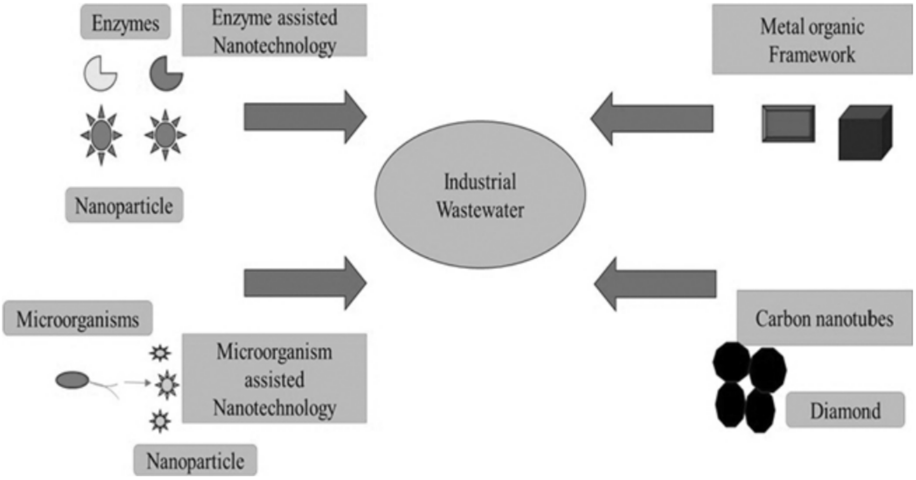
Aspergillus tubingensis, which is obtained from the rhizosphere of *Avicennia officinalis* in the Indian Sundarbans, was used to extract iron oxide nanoparticles. The produced nanoparticles removed more than 90% of the heavy metals [Zn (II), Cu (II), Ni (II), and Pb (II)] from wastewater after five cycles of regeneration capacity. The metal ions were chemically adsorbed on the surface of nanoparticles by endothermic reaction [42]. Iron oxide and exopolysaccharides (EPS) from *Chlorella vulgaris* were co-precipitated in a different investigation. EPS functional groups were shown to effectively modify the nanoparticles and were discovered using Fourier-transform infrared spectroscopy (FT-IR) research. Furthermore, it was demonstrated that the nanocomposite could remove 91% of PO_4^{3-} and 85% of NH4^{+} [47].

The copper-resistant bacteria *Escherichia* sp. SINT7 were used for the synthesis of copper nanoparticles. It was exemplified that the biogenic nanoparticles broke down both and azo and textile effluent dyes. Dyes like reactive black-5, direct blue-1, Congo red, and malachite green were lowered to 83.61%, 88.42%, 97.07%, and 90.55%, respectively, at a low concentration of 25 mg/L. At a concentration of 100 mg/L, these were further reduced to 76.84%, 62.32%, 83.90%, and 31.08%, respectively. The suspended particles, chloride, and phosphate ions in treated samples decreased, and industrial effluent was also treated. Such biogenic nanoparticles' performance supports industry's efforts to produce goods in an economical and sustainable manner [48]. Some of the microorganisms associated with removal of industrial waste pollutants are listed in Table 13.2.

TABLE 13.2
Microbial-Assisted Nanotechnology

S. No	Nanoparticles Synthesized	Microorganism Assisted	Degradation Capacity	Important Features	Reference
1	Zirconia (ZrO_2 NPs) nanoparticles	*P. aeruginosa*	Degradation of tetracycline 526.32 mg/g	Involved in bioremediation and green synthesis of nanoparticles.	[34]
2	Silica nanoparticles	*Actinomycetes*	80% decolouration of industrial dye	Economical and long lasting	[49]
3	Enzyme immobilized nanoparticle	*Pleurotus ostreatus*	Degradation of 90% of bisphenol-A and 10% of carbamazepine	Economical, reusable enzyme	[50]
4	Cobalt oxide (Co_3O_4) and cobalt nanoparticles		Removal of murexide dye 39.4% and 43.6%	More economical, simpler, easier to produce, and more efficient in photocatalysis degradation	[51]
5	Cyclodextrin fibres	*Lysinibacillus sphaericus*	Chromium degradation (VI) = 58% ± 1.4% Nickel (II) = 70% ± 0.2%,	Cyclodextrin offers an additional source of carbon for the growth of bacteria.	[52]
6	Iron oxide nanoparticles	*Aspergillus niger* BSC-1	Degradation of 99% of cr VI		[53]
7	Cadmium sulphide nanoparticles	*Pseudomonas aeruginosa* JP-11	Degradation of 88.66% Cd (II)		[28]
8	Palladium nanoparticles	*Spirulina platensis*	Degradation of 90% Pb		[54]
9	Iron oxide nanoparticles	*Aspergillus tubingensis* STSP 25	Degradation of 98% of Pb(II), 96.45% of Ni(II), 92.19% of Cu(II), 93.99% of Zn(II)		[53]

In another study, Cheng et al. [55] synthesized iron–sulphur nanoparticle. Through the extracellular transport of electrons, these nanoparticles were able to degrade napthal green B dye. The synthesis of nanoparticles using *Pseudoalteromonas* sp. CF10-13 provides a sustainable method of biodegradation. Endogenous nanoparticle synthesis impeded the production of hazardous gases and metal complexes. Utilizing biogenic particles is an excellent approach for cleaning up industrial effluents. There are several ways that microorganisms might contribute to the development of nanotechnology, in addition to their direct ability to produce nanoparticles. For example, microbes when combined with nanoparticles produce catalytic enzymes that aid in the cleanup of effluents. Figure 13.7 explains the various approaches of industrial wastewater treatment using nanotechnology in combination with microorganisms.



▶ Long Description for Figure 13.7

FIGURE 13.7 Different nanotechnology methods combined with microorganisms. ⏎

13.7 FUTURE PERSPECTIVES AND CONCLUSION

Researchers are interested in nanotechnology because of its numerous positive impacts, including its vast surface area, adaptability, durability in difficult environments, ease of handling materials, greater interaction, and several more. The combination of nanotechnology with microbes and enzymes has enabled an environmentally friendly method of treating industrial wastewater. Using microorganism can reduce the risks associated with chemically generated nanoparticles. The residues are separated by precipitation method and simple filtration technique, and they are found to be biocompatible. The commercialization of various components of nanotechnology presents a bigger hurdle. One percent of these aspects of nanotechnology have been introduced to the market. Thus, the large-scale application of these simple and effective microorganism combined with nanotechnology techniques is found to be a springboard for industry. An environmentally sustainable method for bioremediation of industrial wastewater has been made possible by microbial-assisted nanotechnology. The synthesis of nanoparticles from microbes offers better options for sustainable and affordable industrial wastewater treatment. To fully realize the potential of this method, further commercial research and development should be done. This will generate more green energy and strengthen the industrial economy.

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