Nanotechnology for Bioremediation of Industrial Wastewater Treatment

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Abstract At an ongoing pace, the population of the world will increase manifold. The population explosion and global warming will impact the available useful water for drinking. Simultaneously to fulfil the demand of other sectors like industries and agriculture there will be pressure on water availability on earth. Due to human activity, various pollutants are released from the industrial sector. Quick attention is needed towards the treatment of the wastewater before it gets released into the environment to maintain the quality and purity of water. For the treatment of wastewater, various methodologies have developed in the last few years. One of the most interesting ways to treat wastewater is the use of nano bioremediation. The present book chapter enlightens the use of nanotechnology-based bioremediation for wastewater treatment. Nanobioremediation is a method or process in which a combination of biology and nanotechnology is used to remove heavy metal pollutants from wastewater and make water clean. The removal of environmental contaminants (such as heavy metals, organic and inorganic pollutants) from contaminated sites using nanoparticles/nanomaterials formed by plants, fungi, and bacteria with the help of nanotechnology is called Nano bioremediation. In traditional ways using either nanotechnology-based or biological-based methods, these

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M. P. Shah (ed.), *Modern Approaches in Waste Bioremediation*,
https://doi.org/10.1007/978-3-031-24086-7_14

both are capable of removal of toxic metals from the environment. Using nanoparticles along with microorganisms acts synergistically for the removal of pollutants. Sometimes a single enzyme is also effective for bioremediation but the enzyme is not stable. Using functionalized nanoparticles will provide stability and improve bioremediation speed.

Keywords Nanotechnology · Nano bioremediation · Industrial wastewater treatment · Environmental science

1 Introduction of Nano Bioremediation for Industrial Wastewater Treatment

The need for water is just as important as those for food, shelter, and clothes for human beings. Water is indispensable to our existence and life originated here without it, we cannot exist. While water is a natural resource, its availability is limited. According to reports, one of the six individuals has difficulty getting fresh water. It is estimated that until 2025, around 50% of the global population will suffer from water-related issues (Aguilar-Pérez et al. 2021). Clean water is essential for all creatures on the planet. Water access can impact the environment and climate change if there is no proper access. Lack of water will affect biodiversity and destroy habitats in addition to causing landscape erosion (Hashem 2014). With the increase in population, rapid commercialization, and less precipitation, hazardous chemicals have spread across the earth's surface and are affecting the groundwater system. As a result, ecosystems have undergone drastic changes (Zekic et al. 2018). The scarcity of pure water is the primary problem throughout the world, so there is a need to explore new methods and technologies for cleaning water. One method is to use nanotechnology to clean wastewater. During the past few years, water pollution has received a lot of attention. By providing quality water, people will be able to satisfy their current needs for water (Pandey 2018; Shah 2020a, b).

Nanoscience and nanotechnology are experiencing a new era of opportunities due to technological developments. Nanoscience is a branch of science that deals with molecules that have at least one dimension smaller than 100 nm. Even though nanoparticles are made from metal ions, they behave differently from metal ions (Rizwan and Ahmed 2018).

This chapter mainly addressed nanotechnology-based solutions for bioremediating wastewater. The goal of this chapter is to provide an introduction to bioremediation, different methods of bioremediation, nanobioremediation, and different kinds of nanoparticles used in bioremediation, their role, drawbacks, and conclusion.

Before we look at nanotechnology-based wastewater treatment, we should get a better understanding of water pollutants, their sources, types, and effects, as well as the methods used to remove contaminants from water.

1.1 The Main Source of Water Pollutants

Chemical and biotechnological industries produce a variety of useful products. There is no doubt that industries produce inevitable products, but they are also producing products which are ultimately responsible for a source of pollution. Due to various industrial activities, toxic chemicals are released into water.

Here are a few examples of pollutants released by different industries. They can be classified as organic or inorganic. Chlorinated phenols, phthalic esters, persistent organic pollutants (POPs), azo dyes, petroleum hydrocarbons, pesticides, etc., are among the most common organic pollutants. In contrast, inorganic pollutants include heavy metals such as aluminum (Al), cadmium (Cd), nickel (Ni), chromium (Cr), lead (Pb), and mercury (Hg) (Hussain et al. 2016; Bharagava et al. 2020).

Organic Pollutant: Their Sources, and Effects

Chlorinated Phenols

Chlorinated phenols is a major constituent released by coking plants, oil refineries, resin manufacturing, paper and pulp industries. They are recalcitrant and toxic, and the level of chlorination determines their toxicity (Annachhatre and Gheewala 1996; Shah 2021a, b).

Phthalic Esters

They are a class of organic refractory plasticizers used in various products such as plastic roofing, piping, gaskets, medical equipment, rainwear, plastic film. The phthalic ester in plastics is responsible for its flexibility. More than one million tons of phthalic ester is used in the manufacture of plastic in China. It has a serious effect on human health as these compounds are mutagenic and affect the embryonic development of the foetus (He et al. 2015).

Persistent organic pollutants (POPs)

Persistent organic pollutants (POPs) consist of different chemical groups that require attention. Polychlorinated dibenzo-p-dioxins, dibenzo-furans (PCDD/Fs), polychlorinated biphenyls (PCBs), and heptachloride present in pesticides require special attention. Forest fire and volcanic activity are main natural sources of POPs such as dibenzofurans and dioxins. POPs can also be produced by furnaces, incinerators, power plants, and heating systems used in industrial sites. Various countries have banned this type of chemical in recent years. These are organic compounds that are harmful to the environment. POPs are mainly non-biodegradable and lipophilic. It affects the respiratory, circulatory, and digestive systems of the human body (Alshemmari 2021).

Azo Dyes

In many industries, dyes are used as colouring compounds. Colour-producing compounds are classified according to their use and chromophore group. Phytocyanine dyes, anthraquinone dyes, azo dyes and phthalocyanine dyes are chromophore-containing dyes. An Azo dye has a special azo bond responsible for absorbing light in visible wavelength regions.

More than 3000 types of dyes are available on the market. Each year, more than 2.8 tons of dyes are added to the water system. The reason why so many dyes are available is that they are chemically stable and easy to synthesize. A number of industries use azo dyes, including food, paper, leather, cosmetics, textiles, pharmaceuticals. According to the survey, the dye which is used in the dyeing process is not completely utilized, about 10% of the dye is not utilized and unutilized dye discharges into water bodies. These azo dyes released from effluent have many side effects. It damages the cells of the organism, the rate of photosynthesis is reduced, it leads to a decrease in oxygen content which affects the flora and fauna of water bodies. Mainly azo dye consists of a nitro group which is responsible for mutation. When dye is released from industrial water, it breaks down and forms a new kind of toxic product. Such products are mutagenic and carcinogenic. Several derivatives of azo dye after breakdown are o-toluidine, 1,4-phenylenediamine, and 3-methoxy-4-aminoazobenzene which are carcinogenic. According to a study, unsulfonated azo dyes are more toxic and mutagenic than sulfonated azo dyes (Singh and Singh 2017).

Petroleum Hydrocarbons

The oil industry releases wastewater that contains a lot of hydrocarbons, ethylbenzene, benzene, xylene, toluene, small amounts of oxygen, sulfur, nitrogen, and heavy metals. The presence of these hydrocarbons in terrestrial systems or on land changes the original composition of soil and affects the growth of plants. Through different transport processes occurring in nature, petroleum hydrocarbons eventually end up in the sea and pollute marine ecosystems. As a result of fuel spills, large environmental losses occurred in cold regions and threatened the health of organisms. These large numbers of hydrocarbons are responsible for damage to the central nervous system and also lead to suppression of bone marrow activity. In order to remove this kind of contamination from contaminated sites, nanoparticle-based tools can be used (Mohammadi et al. 2020).

Inorganic Pollutants

Industrial wastewater from different sources contain different kinds of heavy metals, such as copper, cobalt, cadmium, chromium, lead, iron, zinc, nickel, and magnesium. Metals such as manganese, copper, zinc, nickel, cadmium, mercury, lead, aluminium, chromium, iron, and cobalt require immediate attention, according to the WHO.

Many countries are concerned about the release of metals or heavy metals into industrial water because these metals or heavy metals persist in the environment and lead to bioaccumulation. Their non-biodegradable nature makes them responsible for continuous transfer into the next generation if they bioaccumulate in organisms. Radioactive metals can cause harm to the human body if they accumulate in the body (Bernard 2008; Assi et al. 2016; Hussain et al. 2016; Koul and Taak 2018a; Magrì et al. 2018).

Here, we will discuss different types of metals, their sources, and their effects on the environment.

Zinc

Industries like coal mining, steel processing, and waste combustion emit zinc. A direct accumulation of zinc causes diarrhoea and gastrointestinal distress, while inhalation of zinc fumes causes fever.

Nickel

Fossil fuel combustion, metal plating industries, nickel mining, electroplating fumes from alloys used in welding and brazing, and nickel-refining industries release nickel. Nickel acts as a carcinogen and causes respiratory tract disease.

Mercury

In paper and pulp manufacturing, gold extraction, chloro-alkali operations, smelting operations, and amalgam tooth fillings, mercury is released. It leads to kidney damage. As a result of chronic poisoning, the blood's ability to carry oxygen is reduced. Mercury can also cause nutritional disturbances, excessive irritation of tissues, loss of appetite, gingivitis, and excessive salivation. Exposure to mercury fumes may cause respiratory problems.

Manganese

Steel and welding industries release large amounts of manganese. Consequently, neurotological disease is caused by this metal. Poisoning can lead to irritability and speech problems.

Lead

Rubber production, glass polishing, jewellery making, lead-glazed plastic manufacturing, stained glass crafting, pottery, and painting make up this industry. Lead affects many different organs of the body. The toxins not only damage organs, but also affect cellular mechanisms and enzymes.

Iron

It includes Hematite mining, metal industries, and welding. Lung silicosis is caused by iron fume accumulation in heavy fumes.

Copper

Copper emissions are mainly caused by welding, copper mining, and metal fumes from smelting operations. Copper causes Wilson's disease and anaemia as well as higher accumulation of copper in the body. Aside from kidney and liver damage, other vital organs can also be harmed and it affects digestion also. At high levels, sulfate and copper induce necrosis and kill the organism.

Cobalt
Paints and cement are the main industries that use cobalt. At low concentrations, it causes respiratory problems such as irritation of the respiratory tract, while at high concentrations, it may cause pneumoconiosis.

Chromium
Chromium is mainly used in paint and colouring companies. Moreover, it is released in the manufacturing of chemical and refractory materials, cement manufacturing, chrome plating, ferrochrome manufacturing, metal finishing industries, combustion of fossil fuels, tanneries, and textile plants. It damages kidneys when at low concentrations, while causing respiratory chromogenic substances when at high concentrations, which are mostly carcinogenic and also cause allergies.

Cadmium
Cadmium is released by several industries, including the automotive and aircraft industries, alloys' production, metallurgy processing, nickel–cadmium battery manufacturing industries, paint industries, plastic industries mining, and textile printing industries. Inhalation and ingestion can cause acute and chronic toxicity. A number of metabolic pathways are affected by Cd, including alcohol dehydrogenase, pyruvate dehydrogenase, pyruvate decarboxylase, delta-aminolevulinic acid dehydratase, arylsulfatase, and lipoamide dehydrogenase.

Aluminium
The production of aluminum alloys, the pharmaceutical industry, and packaging units release aluminium. Humans can develop lung fibrosis from the fumes from these sources. Fumes from these sources can cause lung fibrosis and osteomalacia. Large accumulations in bones can cause lung fibrosis.

Contaminated water also contains microorganisms in addition to organic and inorganic pollutants. These microorganisms are present in wastewater from the healthcare industry because of improperly sterilized medical swabs, needles, and bandages. In normal water bodies, unsterilized tools make the water contaminated.

1.2 The Science Behind the Use of Nanomaterials in Bioremediation

The goal of remediation is to remove toxic, heavy metal, and harmful waste from the environment. The three main methods of environmental remediation are physical, chemical, and biological (Singh et al. 2020).

Remediation of the environment usually involves chemical methods such as reduction, chemical washing, chelating flushing, ion exchange, electrowinning, adsorption, membrane filtration, and concentration. There are a number of biotechnology methods that remove pollutants from the environment, including rhizofiltration, bioslurping, windrows, biosorption, land farming, bioplies, bioventing, bioleaching bioreactors, biosparging, composting, bioaugmentation, biostimulation phytoremediation, and mycoremediation. Among these three major processes, biological processes are the most commonly used because they do not involve toxic chemicals or energy consumption. In most cases, bioremediation does not require the use of external chemicals, as the process relies on naturally occurring plants and microorganisms (Yadav et al. 2017).

Bioremediation can be classified into two major categories: in-situ and ex-situ. In situ bioremediation occurs at the original site where contaminated and toxic substances were excavated before being treated. As a result, it is faster, easier, and more effective than ex-situ bioremediation (Singh et al. 2020).

In soil, there are bacteria capable of degrading soil chemicals. These bacteria are called “bugs”. These tiny bugs are often found in oil spills and gasoline. Microbes can digest chemicals and then convert them into harmless forms, such as water and carbon dioxide. The process occurs in two different ways. As an initial step, it is necessary to manipulate parameters such as nutrient levels, temperature, and oxygen ions in order to increase the ability of microorganisms to digest harmful metals. Adding microorganisms to contaminated sites is the second method, which is not the most common. The two methods serve the same purpose, however (Yadav et al. 2017).

In bioremediation, pollutants are removed from the environment. Nanobioremediation involves removing pollutants from the environment using nanoparticle-based solutions made from plants, fungi, or bacteria.

In their talk, Richard Feynman introduced the concept of nanotechnology. In a talk titled ‘There’s Plenty of Room at the Bottom,’ he did not use the term nanotechnology directly. Nanotechnology is a milestone in the development of new branches of science. Nanotechnology creates new materials by manipulating materials at very small scales. Reduced metal ions have completely different properties than their original forms. Nanoparticles or nanomaterials differ in two important ways; the first is the surface area ratio, and the second is the quantum effect. In order to effectively remove contaminants, both of these factors are necessary. Quantum effects accelerate response time, and when there is a large surface area, the interaction is greater (Mourdikoudis et al. 2018; Rizwan and Ahmed 2018). Based on its applications, nanotechnology can be classified into many branches. In wastewater treatment, a variety of nanomaterials are used. In order to remove pollutant size dependence, nanoparticles play a vital role. Nanoparticles possess special properties that make them suitable for use in different methods of removing contaminants.

Another sub-branch of nanotechnology is green nanotechnology. Eco-friendly nanoparticles and nanoproducts can be made with green nanotechnology. Nanoparticles are most efficient at removing contaminants, which requires fewer resources, in wastewater treatment. These simple, cost-effective processes can be used to remove contaminants from wastewater (Alshemmari 2021).

Nanotechnology-based solutions are widely used in bioremediation because they can be easily synthesized and are safe. In addition, nanoparticles increase the efficiency and speed of bioremediation.

The following examples illustrate how bioremediation works. Phytoremediation involves using plants to eliminate toxic pollutants. Nanoparticles functionalized with specific enzymes will produce the greatest productivity. The procedure is essentially very straightforward. Plants cannot degrade large molecules such as oligosaccharides and large chain hydrocarbons. Plants degrade these complex molecules into simple molecules, which are then degraded by nanoparticles. With this method, bioremediation will be more effective if it is combined with nanoparticles. *Shewanella oneidensis* introduced into a contaminated site with Pd(0) deposition on the cell wall is another good example of nano bioremediation. As a result of their smaller size particles and semipermeable nature of the plasma membrane, these particles also enter the cytoplasm. As well as showing the presence of electron donors such as hydrogen acetate, it will also charge and show the presence of chlorine in water bodies. In addition to acting as indicators, they degrade chlorine (Singh et al. 2020).

1.3 Outline of the Nano Biosynthesis Mechanism Used in Bioremediation

Heavy metals can be removed from a variety of sources using nanoparticles. Nanoparticles are first synthesized using different synthesis methods such as physical, chemical, and biological, and then they are used in bioremediation. Alternatively, nanoparticles can be engineered to combine with microbes, and then these engineered nanoparticles can be used in bioremediation (Koul and Taak 2018a).

There are variety of methods and techniques that can be employed to remove toxic heavy metals from the environment. Bioremediation using nanoparticles/nanomaterials created by plants, fungi, and bacteria with nanotechnology is called nanobioremediation (NBR). There are differences between normal and nano-bioremediation. In remediation, biological agents are typically used, but when combined with nanoparticles, their efficacy is increased. NBR is the most suitable and environmentally friendly method for removing pollutants. As of now, remediation techniques are either *in-situ* or *ex-situ.* Plants, microbes, and enzymes present in organisms that use these techniques for remediation degrade heavy metals. Heavy metals are naturally absorbed by some plants through their roots; this process is known as phytoremediation (Rizwan et al. 2014). When nanoparticles made from plants, microbes, and enzymes were applied, the plant's phytoremediation efficiency was enhanced. Phytoremediation uses enzyme-functionalized nanoparticles in order to degrade long-chain hydrocarbons. Plants and microbes cannot degrade these long-chain hydrocarbons (Shah 2020a, b).

In addition to wastewater treatment, nanoparticles are also used to treat contaminated soil and air pollution (Ibrahim et al. 2016) (Fig. 1).

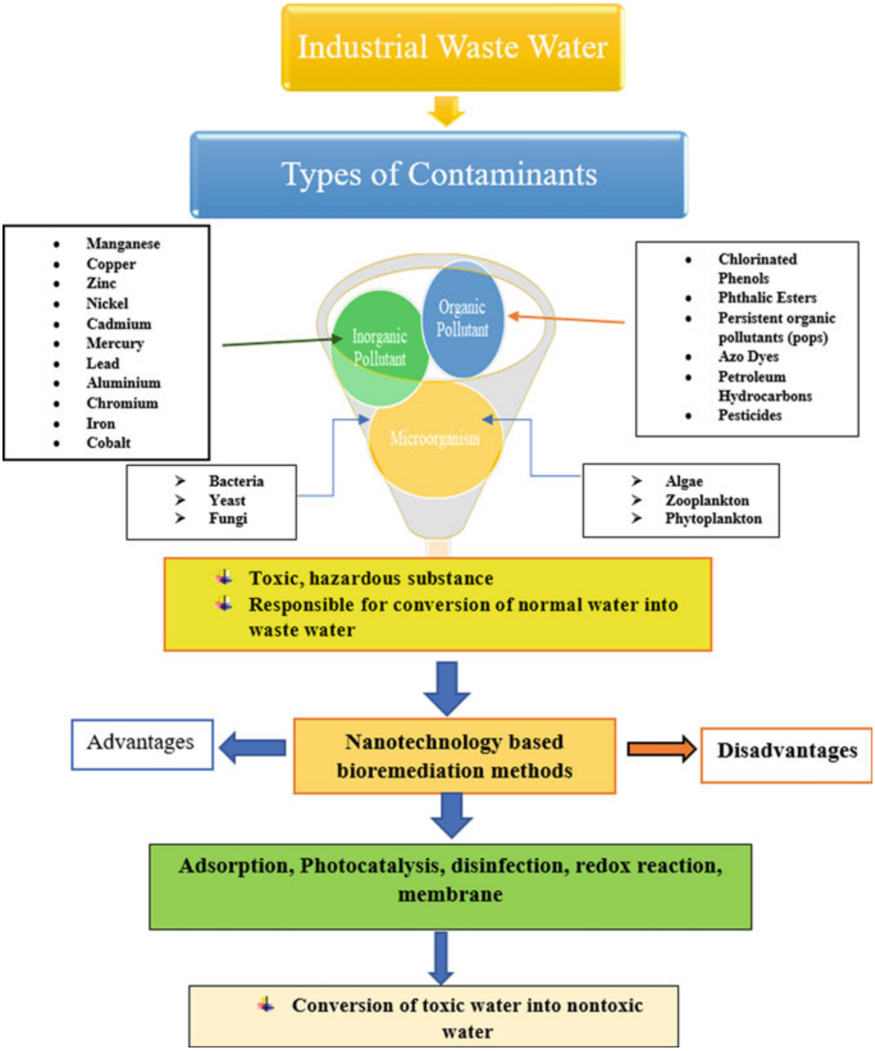

Fig. 1 Outline of bioremediation process for industrial waste water

2 The Method Used in Bioremediation of Wastewater

Several methods are available for wastewater treatment, including adsorption, photocatalytic degradation, redox reaction, disinfection and membrane-based techniques. Due to the unique properties of nanoparticles, such as strong absorption, high reactivity, and quantum size effect, these techniques are widely used (Yadav et al. 2017) (Fig. 2).

2.1 Adsorption

This is a surface-based method for removing pollutants. An adsorption process occurs when adsorbable solutes interact with solid adsorbents. Nanoparticles serve as solid adsorbents, whereas heavy metals serve as adsorbable solutes. Due to the interaction force between the adsorbent and adsorbable solute, adsorbable solute deposits on adsorbable surfaces. Adsorption stands out for wastewater treatment because of its versatility, unique properties, superior efficacy, large surface area, multiple adsorption sites, temperature-dependent modifications, specific pore sizes, unique surface chemistry, ease of handling, low cost, and the fact that it does not require pretreatment. Shape and morphology also play an important role in nanobioremediation. Because of their high absorption capacity, modified nanosorbents can sometimes become toxic (Ali and Gupta 2007).

In the removal of heavy metals, adsorbents play an important role. Nano adsorbents like activated carbon, clay minerals, and natural zeolites can also remove heavy metals, but their adsorption capacities are low, resulting in poor results. Nanoparticles with sizes of 1-100 nm are often used in bioremediation instead of traditional sorbents. Chemical, physical, and biological methods can be used to synthesize nanoadsorbents. Biosynthesis materials are widely used because they do not require toxic chemicals or high energy. Chemistry and physical synthesis nanoparticles have a well-defined shape and size, while biological synthesis nanoparticles require special

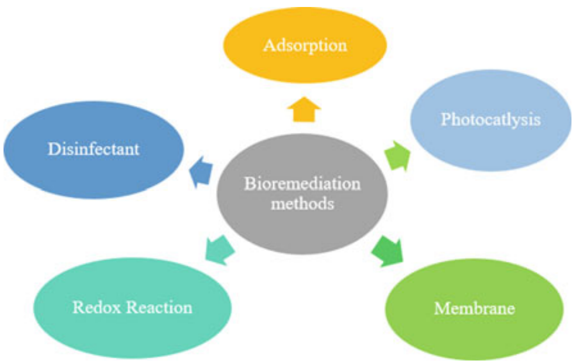

Fig. 2 Method used in Bioremediation

attention to their shape and size. In the biological synthesis of nanoadsorbents, plants such as algae, bryophytes, angiosperms, microbes, and enzymes secreted by living organisms are used as reducing agents. Functionalized nanoparticles can be synthesized intracellularly or extracellularly by secreting enzymes from the organism where they function to reduce metal ions and stabilize them (Mourdikoudis et al. 2018).

Nanoadsorbents such as nanotubes, nanowires, and quantum dots are used to treat wastewater. Nanoadsorption is currently performed with nanoparticles of zero-valent metals, metal oxides, and nanocomposites. The most commonly used nanoparticles in wastewater treatment are titanium oxides, cerium oxides, manganese oxides, nanosized zero-valent metals, ferric oxides, aluminium oxides, and magnesium oxides. Phosphate, an organic pollutant, can be selectively absorbed by cerium oxide. Metallic nanoparticles are known for their simplicity, super magnetic properties, and high adsorption capacities, which make them ideal for remediation. Besides adsorption, chemical and photodegradation methods are also used for wastewater remediation. However, metallic nanoparticles also have some disadvantages, such as their small size, which makes them less stable, causing agglomeration, and reducing their properties. Further, separation from water bodies is difficult, and higher deposition causes toxic effects on water ecosystems (Aguilar-Pérez et al. 2021).

The pharmaceutical industry uses a variety of drugs that are released into the environment. Pharmaceutical drugs can disrupt the body's homeostasis as well as the endocrine system. In addition, these products produce a large amount of free radicals, which are toxic. If these medications are used excessively, they can cause genotoxicity and immunosuppression. For instance, Ibuprofen, paracetamol, and diclofenac do not require a prescription. Paraben, which is found in many skincare products, is another pharmaceutical drug that causes environmental problems. Medically, diclofenac is used to disinfect wounds, but it produces antibiotic-resistant bacteria that cannot be killed by any antibiotic. The drug is also responsible for the emergence of drug-resistant bacteria (Sherry Davis et al. 2017).

The first report on carbon nanotubes was published by Iijima in (1991). As cylinder-shaped macromolecules, CNTs have a radius as small as a few nanometres and varying lengths. CNTS are hexagonal lattices of fullerenes with grooves. These highly hydrophobic nanoparticles are used in wastewater treatment because of their ability to entrap organic molecules due to the hydrophobic aggregation between them (Roy 2014a).

In a recent study, green-synthesised Cu nanoparticles were effective at removing three selected pharmaceutical drugs from aquatic media (Husein et al. 2019). Nanoparticles of different types are used in nanobioremediation. Metal nanoparticles of Ag, Au have good degradation properties for organic dyes (Sherry Davis et al. 2017). Bimetallic Fe/Ni nanoparticles of size 60–85 NM produced by green synthesis can remove 85.8% of triclosan from wastewater. By using biologically produced platinum and palladium nanoparticles from *D. vulgaris*, other pharmaceutical drugs, such as sulfamethoxazole, have been successfully removed. It is capable of removing 85% of the contaminants (Sherry Davis et al. 2017).

Nanoparticles can be produced using plants such as *Noaea mucronata, Euphorbia maroclada,* which can remove Pb, Cd, Zn, Cd, and Ni. Nanoparticles can also be produced by bacteria. For the removal of toxic metals, iron nanoparticles are effective.

Maghemite is a type of iron nanoparticle produced by *Actinobacter.* A study found that bacteria produce iron nanoparticles aerobically and participate in bioremediation. Additionally, thermophilic nanoparticles can be used to create magnetic nanoparticles that degrade heavy metals. nZVI nanoparticles produced from black tea, grape marcs, and vine leaves remove ibuprofen from an aqueous medium (Koul and Taak 2018a).

The orange peel powder has also been used to synthesize Fe_3O_4 nanoparticles with good adsorption capacity of cadmium from an aqueous solution. According to a comparative study of orange peel powder, chemically produced magnetic nanoparticles and orange peel-mediated magnetic nanoparticles, they have surface areas of 47.03, 76.32 and 65.19 m^2g^{-1} BET respectively (Ali 2017).

Nano clay is also used in the absorption process. In addition to removing contaminated water, these nano clays are used in soil bioremediation. Nano clay is used for the successful reduction of phosphorus, according to a report by Allophane. According to this study, phosphorus concentration reduces from 14.2 to 4.2 mg/L, a reduction of nearly 70% from the original medium (Koul and Taak 2018a).

2.2 Photocatalysis

In this process, UV light is used to oxidize organic pollutants and convert them into water and carbon dioxide as by-products. Photocatalysis can also be used to disinfect certain bacteria. During photolysis, the photocatalyst area accelerates the reaction rate without consuming it. It is an advanced oxidation process (Ibrahim et al. 2016) where nanoparticles act as photocatalysts. By absorbing UV light, photocatalysts get charged and can convert hazardous, non-biodegradable contaminants into non-hazardous, biodegradable compounds. Using light to convert contaminants has advantages and disadvantages. Reaction rates may increase or decrease as a result of light. In case of low light intensity, reaction rate and photocatalytic activity are affected. As photocatalysts, different nanoparticles are used, such as TiO_2, Si, Cd, ZnS, SnO_2, WSe_2, Fe_2O_3, WO_3, TiO_3, ZnO, etc. (Roy 2014b) (Fig. 3).

A photocatalytic material is typically illuminated with light that balances the valence and conduction bands during the photolysis process. Exposure of light photons to irradiation is more powerful than their band gap energy. As a result of this process, electronic holes are created, which combine with organic pollutants and produce reactive oxygen species. In photocatalysis, the size of the nanoparticles plays a crucial role (Aguilar-Pérez et al. 2021). Water molecules capture the hole (hh) generated by electron–hole pairs in photocatalysis. By releasing hydroxyl radicals (OH-) from water molecules, a wide range of microbial cells and organic pollutants can be degraded. There has been a great deal of interest in the role of titanium nanoparticles and silver in environmental bioremediation, especially in wastewater treatment (Ojha 2020).

Fujishima and Honda discovered the photocatalytic thin-film mechanism while studying the electrochemical photolysis of water on TiO2 semiconductor electrodes.

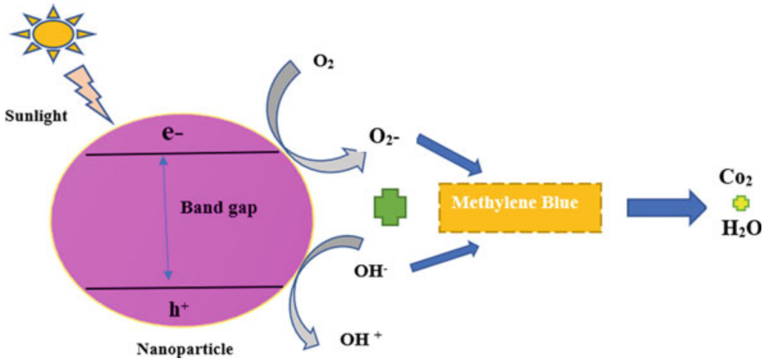

Fig. 3 Degradation of Methylene blue through photocatalysis

The titanium nano-oxide nanocomposite inactivates microorganisms by UV irradiation (Berekaa 2016). To enhance the photocatalytic activity of nanoparticles, titanium quantum dots (QDs), titanium nanotubes, titanium nanosheets, titanium nanowires, and titanium mesoporous hollow shells are used. Different morphological forms of Tio2 increase the number of photoreactive sites exposed. TiO2 nanoparticles with metal or non-metal doping should enhance charge separation or board the absorption spectrum. In addition to difficult recovery, agglomeration, and short activity, titanium oxide nanoparticles have several disadvantages (Ibrahim et al. 2016).

Copper nanoparticles are synthesized from Escherichia sp SINT7, which is copper resistant. The nanoparticles successfully degrade azo dye at a very low concentration of 25 mg g^{-1}. A blank Cango-T shows a reduction of 83.61%, while Direct Blue-1 reduces up to 88.42% (Mandeep and Shukla 2020). In addition to their function as a semiconductor, Zn NPs are also used as a photocatalyst to degrade organic dyes, phenols, and pharmaceuticals (Sherry Davis et al. 2017).

2.3 Redox Reaction

During wastewater treatment, an oxidation and reduction reaction takes place because of the redox reaction conversion of hazardous contaminants or toxic metals into non-hazardous contaminated or nontoxic metals that become more stable, less mobile, or inert. To enhance degradation and extraction capacity, redox reactions are used in remediation to change the water chemistry and microbiology by introducing specific substances into wastewater containing contaminants.

Water contaminated with organic or inorganic contaminants can be treated with this redox process technique. It is not only laboratory practice used for bioremediation, but all processes on earth use energy generated from redox reactions (Tandon and Singh 2016).

On earth, basic transformations such as the nitrogen cycle, carbon cycle, sulphur cycle, magnesium cycle, iron cycle, and nitrous cycle take place. Redox-sensitive elements such as chromium (Cr), arsenic (As), uranium (U) and copper (Cu) may be present in the environment (Tandon and Singh 2016). Redox-active CeO2 nanoparticles are used for the treatment of wastewater in a variety of industries. Redox nanoparticles react with Cr (VI) (aq) and Fe2+ species, leading to the change in surface morphology (Division 2019). As part of traditional methods, chlorine and ozone are used to disinfect; this product produces carcinogenic substances. By using nanoparticles, these problems are solved. Ferrate (VI) is used as a disinfectant for algae, bacteria, microcystins, viruses. Many natural and advanced nanomaterials exhibit disinfectant properties. Nanoparticles such as silver nanoparticles, chitosan, photocatalytic TiO2, aqueous fullerene nanoparticles and carbon nanotubes, fullerol interact with the cell membrane and cause the membrane to break down and release reactive oxygen species. Nickel, selenium, chromium, cobalt, arsenic, lead, and copper are easily controlled by redox reactions in order to determine their toxicity and mobility (Tandon and Singh 2016).

2.4 Disinfection

Water emitted from various sources contains many pathogens that may cause serious health problems in humans. Bacteria (*Escherichia coli, Pseudomonas aeruginosa, Burkholderia pseudomallei, Salmonella typhi, Plesiomonas, Yersinia enterocolitica, Vibrio cholera, Campylobacter spp., Shigella spp.*, etc.),cyanobacteria (*Anabaena, Nostoc*, Microcystis, Planktothrix), viruses (astroviruses, hepatitis A viruses, hepatitis E viruses, noroviruses enteroviruses, sapoviruses, rotavirus, adenoviruses), prions, protozoa (*Cyclospora cayetanensis, Isospora belli, Entamoeba histolytica, Giardia intestinalis, Cryptosporidium, Balantidium coli, Naegleria fowleri, Toxoplasma Gondii, Acanthamoeba spp.*), helminths (*Schistosoma spp., Dracunculus medinensis*), cysts, fungi, Rickettsia, etc., are various kind of microbes that pose a serious threat to people and ecosystems alike (Ojha 2020). Water treatment must be done properly. It is one of the simple processes in which microorganisms are killed by suitable compounds and water becomes free of microorganisms. The use of disinfectants is not limited to eliminating microbial contamination; they also help eliminate other parameters like colour, taste, oxidize iron and manganese in water bodies, and enhance filtration as well as coagulation activity (Berekaa 2016).

These disinfection practices are mostly used in the pharmaceutical industry, medical field, research labs, and diagnosis centers. In traditional disinfection methods, chlorine, ozone is used to kill compound toxics and cancerous byproducts, like halo acetonitrile, dibutyl phthalate, halo acetic acid, chlorite, and chloral hydrate. According to the report, there are about 600 byproducts of disinfection that are very harmful to living things. Nanoparticles are a safer alternative. The silver nanoparticles, zinc oxide, iron oxide, manganese oxide nanoparticles (Mn2O3, MnO2, MnO and Mn3O4) NPs, titanium oxide nanoparticles, cerium oxide nanoparticles, magnesium oxide nanoparticles, silica-based nanocomposites, and carbon-based nanomaterials play an important role as disinfectants either by generating reactive oxygen species or by disrupting cell membranes. Several metals play an important role in the disinfection of E. *coli* bacteria. A superior ability to kill bacteria has been demonstrated by silver nanoparticles (Berekaathe 2016; Ojha 2020).

A Double-layered superparamagnetic Fe3O4@SiO2@Ag@porousSiO2 nanoparticle shows good disinfectant properties against E. *coli, as well as good recycling properties.* It is a two-layer system, with Fe 3 O 4 @SiO 2 nanoparticles on the inner layers and Ag@porous SiO2 nanoparticles on the outer layers. It is believed that the inner layer of Fe 3 O 4 @SiO 2 was protected by a dense silica matrix and allowed Ag to be loaded on the outer surface. The outer mesoporous silica helps to dissolve and oxidize Ag, giving Ag+ ions. Combinational double-layered nanoparticles can meet the MCL for drinking water after treatment (Wang et al. 2019).

The use of titanium nanoparticles led to fast killing of bacteria E coli in the presence of solar irradiation followed by a first order kinetic mechanism. Iron oxide nanoparticles also show great properties, and they are easy to synthesize, cost-effective, and recyclable, which shows great disinfectant properties (Ojha 2020). Titanium nano-oxide and thin-film nanocomposite demonstrated the ability to inactivate microorganisms (Berekaa 2016).

According to a review article, iron granules used on a commercial scale successfully inactivated viruses and nanoscale zero-valent iron (nZVI) particles completely destroyed bacteria like Pseudomonas fluroscens and *B. subtilis.* Hybrid copper and ZVI nanoparticle clusters were used in a case study in Tirupur, Tamil Nadu, India to treat industrial effluents (textile, tannery, pharmaceutical) and sewage. The hybrid cluster uses more copper, ZVI, and less silver to reduce treatment costs. These clusters remove excess salts, fluorides, heavy metals, excess salt, dyes from the effluent (Kiruba Daniel et al. 2014). Nanoparticles may act as an antimicrobial agent for wastewater treatment, along with a combination of UV disinfection to improve water quality (Berekaa 2016).

2.5 Membrane

Using Membrane in wastewater treatment is one of the most effective strategies for removing water pollutants since it has a great separation capacity and does not require the addition of chemicals during operation. The efficiency of membranes is determined by the permeability of the membrane material. Membranes are generally made of cellulose acetate, polyamides, or polyacrylonitrile. In accordance with the size of membranes, there are different categories of membranes. Bacteria, suspended solids, and protozoa are removed by micro membranes. Viruses can be removed with Ultrafiltration, whereas heavy metals and organic matter can be removed with Nanofiltration (Abdelbasir and Shalan 2019).

Fouling of the membrane is a disadvantage of membrane filtration. There are two types of fouling: organic fouling and biological fouling. Organic fouling is a deposition of organic molecules inside the membrane pore, whereas biological fouling occurs when microorganisms present in the water attach to membranes and reduce flux capacity. The limitations of the membrane can be overcome by modifying the membrane with hydrophobicity parameters which are capable of enhancing organic antifouling (Ibrahim et al. 2016).

The use of nanofiltration membranes is a good practice for removing pathogens such as Cryptosporidium oocysts (Ojha 2020). Nanofiltration membranes (NF) not only remove toxic metals, but are also important for recovering nutrients from industrial wastewater. NF with 90 mm pore size is commonly used in paper and pulp industry and has the advantage of rejecting more than 70% of phosphorus. However, the disadvantage of these NF is high phosphorus, which causes fouling of the membrane. Gold nanoparticles embedded with a polymer blend of NF membrane exhibit better recovery, rejection of trivalent phosphate at 96.1%, and increased fouling resistance. Graphene oxide (GO) or attapulgite (ATP) supported on ceramic shows nearly 100% rejection of heavy metals like nickel, lead, cadmium, and copper (Mandeep and Shukla 2020).

As nanotechnology advances, new membranes are developed for water treatment. Grafting, bending, and other methods are used to modify membranes. The modifications are necessary to make the membrane highly permeable, increase catalytic properties, and degrade contaminants (Ibrahim et al. 2016).

The membranes used in bioremediation processes are produced by the electrospinning process, the purpose of using the electrospinning process is to generate polymer or composite nanofibrous membranes from different materials between 20–200 m diameter. Electrospinning provides a fine porous size with a large specific surface area and gives the membranes high water flux. A study revealed that nanomembranes can effectively remove a wide range of heavy metals and after this process, the membrane can be recovered again and reused after cleaning it (Abdelbasir and Shalan 2019).

The affinity of the membrane can be increased by adding a functional group to it. Through covalent interaction, ligands are attached to the membrane for functionalization. Cibacron blue is attached to the cellulose nanofiber membrane for functionalization during aluminium purification. Attaching ceramic nanoparticles such as alumina hydroxide or iron nanoparticles to polymer nanofiber membranes removes heavy metals from the nanofibers. As a ligand molecule, cyclodextrin can also be added to polymethyl methacrylate nanofiber membranes to improve the removal of organic waste (Ibrahim et al. 2016). Nanoparticles can be used individually or in combination with appropriate matrices to remove pollutants from industrial waste water. In a review on Microbial Nanotechnology for Bioremediation of Industrial Wastewater, it was found that porous magnesium oxide can absorb 1000 mg. g^{-1} toxic dye from the iron industry. The grafted iron oxide with hyperbranched polyglycerol had the ability to remove copper, nickel, and aluminium from wastewater in just 35 s (Mandeep and Shukla 2020).

Nanoparticles are supported on suitable supporting materials during the membrane process. For example, cellulose acetate, alginate, and polyvinyl alcohol embedded with silver nanoparticles. Different fabrication processes have been developed based on the separation process. Silver-coated Mn Zn ferrite, silver-containing thermoplastic hydrogels, silver-ion-exchanged titanium phosphate films, and silver nanoparticles within third-generation dendritic poly (amidoamine) (PAMAM) grafted onto multiwalled carbon nanotubes are used in membrane filtration. Many transport mechanisms in bacteria are inhibited by silver ions, which bind to bacterial DNA (Mandeep and Shukla 2020).

Nano-zeolites in Thin Film Nanocomposite Membranes (TFN) increase membrane permeability. 80% of the salt is rejected by these TFNs. Nano-TiO2 in TFCs increases rejection rates, reduces biofouling, reduces biological contaminants, and inactivates microorganisms using UV light (Kiruba Daniel et al. 2014).

3 Nanoparticles Used in Bioremediation

A significant increase has occurred in the biological synthesis of nanoparticles to create new materials that are cost-effective and stable with important applications in electronics, medicine and agriculture. It is possible to synthesize nanoparticles using an array of conventional methods, but biological synthesis is superior because of its ease of rapid synthesis, control, ease of processing, control of size characteristics, low cost, and eco-friendly approach. Biological contaminants (such as bacteria) and chemical contaminants including organic pollutants, are extensively removed with the help of nanoparticles. During the last decade, nanoparticles and nanomaterials have attracted considerable attention because of their unique size-dependent physical and chemical properties (Okhovat et al.2015).

Biological systems can synthesize molecules with highly selective properties and are self-organizing. Nanoparticles produced traditionally by physical and chemical methods are costly. As a way to synthesize nanoparticles at a lower cost, microorganisms and plant extracts were used. Using a bottom-up approach, nanoparticles are biosynthesized by reduction and oxidation reactions. It is usually microbial enzymes or plant phytochemicals with antioxidant or reducing properties that are responsible for reducing metal ions into nanoparticles (Sastry et al. 2003).

3.1 Nanoparticle Synthesized by Plants

The green synthesis of nanoparticles by plants has become very popular in recent years due to a single-step biosynthesis process, lack of toxicants, and presence of natural capping agents. It is advantageous to use plants for the synthesis of nanoparticles since they are readily available, safe to handle, and have a broad range of metabolites. Water-soluble phytochemicals reduce metal ions in a much shorter period than fungi and bacteria (Yadav et al. 2017).

The synthesis of nanoparticles by plants is therefore superior to that of bacteria and fungi. Compiled information indicates that the effects of nanoparticles vary from plant to plant and depend on their mode of application, size, and concentration (Yadav et al. 2017).

Silver Nanoparticles

To remove toxicity from wastewater, silver nanoparticles can be used in simulated wastewater treatment. The plants that have been reported for the synthesis of silver nanoparticle are *Elettaria cardamomum, Parthenium hysterophorus Ocimum sp, Euphorbia hirta, Nerium indicum Azadirachta indica, Brassica juncea, Pongamia pinnata, Clerodendrum inerme, Gliricidia sepium, Desmodium triflorum, Opuntia,ficus indica, Coriandrum sativum, Carica papaya,* (*fruit*) *Pelargonium graveolens, Aloe vera extract, Capsicum annuum, Avicennia marina, Rhizophora mucronata, Ceriops tagal, Rumex hymenosepalu,s Pterocarpus santalinus, Sonchus asper.* Most commonly, silver nanoparticles are used in disinfection techniques due to their toxic effect on microorganisms at certain levels.

Gold Nanoparticles

Heavy metals, fertilizers, detergents, and pesticides seriously reduce the availability of pure drinking water and potable water. Research on several fronts is advancing the idea of nano based solution using gold for cost-effective solution in water treatment, which has intriguing potential to deal with the water pollution problem. The plants responsible for synthesizing the gold nanoparticles are *Terminalia catappa, Banana peel, Mucuna pruriens, Cinnamomum zeylanicum, Medicago sativa, Magnolia kobus, Dyopiros kaki, Allium cepa L., Azadirachta indica A. Juss., Camellia sinensis L., Chenopodium album L., Justicia gendarussa L., Macrotyloma uniflorum, Mentha piperita L. Mirabilis jalapa L., Syzygium aromaticum* (*L*)*, Terminalia catappa L., Amaranthus spinosus* (Li et al. 2011).

The degradation of methylene blue is achieved by using more than 20 plant-mediated gold nanoparticles. Oil of leaves of *Myristica fragrans, Fagonia indica, Persea americana* seed extract*, Nigella arvensis leaf* extract*, Lagerstroemia speciosa, Sterculia acuminate, Mimosa tenuifolia, Salmalia malabarica, Sesbania grandiflora L.,* Edible coconut oil, *Parkia roxburghii,* leaf extract, *Costus Pictus* leaf extract, *Actinidia deliciosa* fruit*, Costus speciosus* rhizome, *Citrifolia* fruit extract*,* *Hydrocotyle asiatica* leaf extract can produce gold nanoparticles and degrade methylene blue under different conditions (Dabhane et al. 2021). Although Gold nanoparticles have been used to degrade dyes in several reports, this process is not commercially viable because the gold salt is expensive and the nanoparticle cannot be recovered after degradation. A commercially viable process could be created by using nanoparticles supported by matrices.

The catalytic activities of gold and silver nanoparticles were determined by catalytic degradation of pollutants with excess amounts of NaBH4 at room temperature. A photocatalytic mechanism can be used to bioremediate industrial water using such nanoparticles (Vo et al. 2019).

CuO Nanoparticle

Plant-mediated copper oxide nanoparticles are the easiest, simple and most efficient way for the production of nanoparticles. *Madhuca longifolia* extract mediated CuO nanoparticles exhibit great characterization aspects like great crystalline nature on XRD and on change in different sizes it shows an increase in photoluminescence property. This nanoparticle shows photocatalytic degradation of methylene blue (Das et al. 2018).

3.2 Nanoparticles Produced by Bacteria

Bacteria produce enzymes that catalyze specific reactions which are responsible for the synthesis of nanoparticles. This provides a new rational biosynthetic strategy that involves the use of enzymes, microbial enzymes, vitamins, polysaccharides and biodegradable polymers. The extracellular secretion of enzymes has the advantage of producing highly pure nanoparticles of size 100–200 nm that are free of other cellular proteins. The properties of nanoparticles are determined by optimizing the parameters controlling organism growth, cellular activities, and enzymatic processes. A large-scale synthesis of nanoparticles using bacteria is attractive because it does not require hazardous, toxic, and expensive chemical materials (Iravani 2014). Bacteria are considered potential sources of nanoparticle synthesis, like gold, silver, platinum, palladium, titanium, titanium dioxide, magnetite, cadmium sulphide, and so on.

Silver Nanoparticles

Silver nanoparticles (Ag NPs) are highly toxic to microorganisms and thus have strong antibacterial effects against a wide range of microorganisms, including viruses, bacteria, and fungi. Silver nanoparticles attached to filter materials have been considered promising for water disinfection due to their high antibacterial activity and cost-effectiveness. The bacteria responsible for the synthesis of silver nanoparticles are

Bacillus cereus, Oscillatory willie, Escherichia coli, Pseudomonas stuzeri, Bacillus subtilis, Bacillus cereus, Bacillus thuringiensis, Lactobacillus strains, Corynebacterium, Staphylococcus aureus, Ureibacillus thermosphaericus (Li et al. 2011). *Pseudomonas aeruginosa* JP-11 was extracted from marine water produced 40 nm, spherical shape cadmium sulphide nanoparticle removes cadmium pollutant from aqueous solution. Other bacteria like *Klebsiella pneumoniae, Escherichia coli, Pseudomonas jessinii isolated from* tiger nuts, carrot juice and faces are responsible for silver nanoparticles. *Shewanella loihica* PV-4, produced spherical shape silver nanoparticle responsible for degradation of methyl orange dye (Gahlawat and Choudhury 2019).

3.3 Nanoparticles Produced by Yeast and Fungi

The fungi are an excellent source of extracellular enzymes that influence nanoparticle synthesis. Many of them have been used for the biosynthesis of nanoparticles. As compared to bacteria, fungi can produce larger amounts of nanoparticles (Munisamy).

It is equally important to understand the nature of the biogenic nanoparticles. As a result of microbiological methods, nanoparticles are formed more slowly than those derived from plant extracts. Enzymes produced by fungi are responsible for synthesis of nanoparticles. Due to the wide diversity, easy culture methods, reduced time, and cost-effectiveness of fungi, they offer an advantage over other methods. Thus, nanoparticles can be synthesized in an eco-friendly manner (Ali et al. 2011).

CuO Nanoparticles

CuO nanoparticles can be produced using fungus-like *Penicillium chrysogenum*. In this study, copper sulfate with fungal extract was exposed to gamma dose radiation. The nanoparticles form were found to be effective against six different kinds of fungi *Ralstonia solanacearum, Fusarium oxysporum, Ralstonia solanacearum, Aspergillus niger, Penicillium citrinum, Erysiphe cichoracearum, Erwinia amylovora, and Alternaria solani.*

Maximum antifungal activity of penicillium-mediated copper oxide nanoparticles was observed in *Fusarium oxysporum* and it was least effective in *Erwinia amylovora.* This nanoparticle is best for disinfection of agricultural packaging tools because these six fungi infects agricultural crops and when it comes to the packaging industry there might be a chance of contamination of water. It is necessary to take action against these fungi for future contamination (El-Batal et al. 2020).

Gold nanoparticles synthesized using fungus *Streptomyces griseoruber* extracted from soil samples of Mercara region are responsible for degradation of methylene blue (Gahlawat and Choudhury 2019).

4 Target Specific Removal of Pollutants Using Nano Bioremediation

Studies are being conducted on removing contaminants from industrial wastewater, which contains various types of contamination. A few examples of nanoparticles that have been used for metal or nonmetal removal from industrial wastewater are shown in Table 1. Industrial wastewater contains major metals and nonmetals such as Cr (VI), Pb (II), Mercury, Cu II, Cd (II) / Pb (II), Ar (III), Nickel, Anionic chromat (Ibrahim et al. 2016) (Puthukkara et al. 2021a).

4.1 Metal or Non-Metal

Chromium VI

1 g/L of guar gum zinc oxide nanoparticles can remove almost 98.63% Cr (VI) within 50 min at pH 7. Green tea leaf extract, *Syzygium jambos* (*l.*)*, Eucalyptus globulus* leaf*, Citrus limetta* fruit peel mediated iron nanoparticles also remove chromium VI from industrial wastewater (Ibrahim et al. 2016).

Pb (II)

A graphene oxide/zinc oxide nanocomposite (GO-ZnO), iron phosphate-mediated magnetite nanoparticle (Fe3O4), and a Syzygium aromaticum flower extract-mediated zerovalent iron nanoparticle (ZIF) have been shown to remove Pb II. The adsorption capacities of CeO2, Fe3O4, and TiO2 are 189 mg Pb/g, 83 mg Pb/g, and 159 mg Pb/g, respectively. The TiO2, Fe3O4 and CeO2 nanoparticles do not show any toxicity, but CeO2 exhibits high phytotoxicity.

Mercury (Hg2+)

Mercury ions are removed by iron sulfide (FeS) nanoparticles synthesised using carboxymethylcellulose (CMC) as a stabilizing agent.

Cadmium (II) / Lead (II)

Cd (II) and Pb (II) were removed from wastewater using NiO nanoparticles. Both heavy metals can be absorbed by the NiO nanoparticles. NiO nanoparticles had maximum adsorption capacities for Pb (II) and Cd (II) ions of 625 mg/g and 909 mg/g, respectively. Contaminants are removed spontaneously and endothermically during this process.

Arsenic (III)

Fe3O4 nanoparticles with ascorbic acid show 46.06 mg/g absorption of arsenic (III) and arsenic (V) from contaminated sites. The advantage of these nanoparticles is that they prevent metals from leaching from water.

Copper (II)

The copper (II) adsorption capacities of ZnO and MgO are 593 and 226 mg/g, respectively, at 3 to 4 pH. Iron phosphate nanoparticles coated with sodium carboxymethyl cellulose can absorb copper (II) from soil and water (Table 1).

4.2 Organic or Inorganic Molecules

Various types of nanoparticles are used for removing organic and inorganic pollutants. They are mostly carbon-based nanoparticles that are used to remove toxic compounds from the environment. Dye, pesticides, benzene/phenol derivatives and pharmaceuticals are among the organic and inorganic pollutants released into industrial water. Table 2 provides data regarding different types of organic/inorganic pollutants, specific contaminants released by different sectors and nanoparticle-based solutions for removing contaminants.

Organic Dyes

Different dyes are eluted in the textile industry. Methylene blue, methylene orange, bromophenol blue, malachite green, Reactive Blue 4 (RB4), Alizarin red S (ARS) and Morin are some of the most common dyes. Due to electrostatic interaction, methylene blue can interact with magnetite carbon nanotubes and exhibit high absorption capacity. Carbon nanotubes (CNT) prepared by acid washing and oxidation of nanoparticles in purified air are used to degrade methyl orange. A high CNT dosage is responsible for inhibiting the surface methyl orange dye molecules. Dye degradation is affected by temperature and pH. Dye-like reactive blue degrades at high temperatures, due to the high temperature, particle diffusion between dye molecules increases, leading to the degradation of the dye. The adsorption capacity of Alizarin red S (ARS) and Morin is increased with low pH.

Additionally, plant extract synthesized nanoparticles are capable of degrading dye molecules. Mango peel, *Cupressus sempervirens, Camellia sinensis,* Green and black

Table 1 Types of contaminant and nanoparticles used in removal of contaminantes

Types of Contaminants	Target specific contaminant	Nanoparticles used in bioremediation	References
Metals /Non-metal	Heavy metals	Thiol-functionalized superparamagnetic nanoparticles, ZnO, FeO3	Ibrahim et al. (2016)
	Cr (VI)	Guar gum–nano zinc oxide (GG/nZnO)	
		Green tea leaf mediated zerovalent iron nanoparticle	
		Syzygium jambos (*l.*) Alston leaf extract-based ZVI nanoparticle	Puthukkara et al. (2021a)
		Eucalyptus globulus leaf	
		Citrus limeta fruit peel	
	Pb (II)	Nanocomposite GO–ZnO(OH)2, Magnetite (Fe3O4)	Ibrahim et al. (2016)
		Iron phosphate mediated nanoparticle	
		Nano ZnO nanoparticle	
		CeO2, TiO2 nanoparticles	
		Syzygium aromaticum flower mediated zero-valent iron nanoparticles	Puthukkara et al. (2021a)
	Mercury	Iron sulphide (FeS) nanoparticle	Ibrahim et al. (2016)
	Copper II	Iron phosphate nanoparticle	
		Magnesium and zinc oxide (MgO and ZnO)	
		carbon nanotube modified with silver nanoparticle	
	Cd (II) / Pb (II)	Nanocrystalline hydroxyapatite (nHA)	
		NiO nanoparticles	
	Ar (III)	Fe3O4 nanoparticles Coated with ascorbic acid	
	Nickel	Carbon nanotube modified with sodium hypochlorite	
	Anionic chromate	Oxidation on carbon nanotube	

Table 2 Nanoparticle used in removal of organic/inorganic pollutant

Organic /inorganic Contaminants	Target specific contaminant	Nanoparticles used in bioremediation	References
Organic dyes	Methylene blue (MB)	Carbon nanotubes loaded with magnetite	Ibrahim et al. (2016)
		Psidium guajava leaf extract-based ZVI nanoparticle	Puthukkara et al. (2021a)
	Methyl orange (MO)	Carbon nanotube	Ibrahim et al. (2016)
		Mango Peel mediated ZVI nanoparticle	Puthukkara et al. (2021a)
		Cupressus sempervirens leaf mediated ZVI nanoparticle	
	Bromophenol blue	*Camellia sinensis* leaf extract mediated zero-valent valent iron nanoparticle synthesis	
	Malachite green	Green, oolong and black tea leaf extract mediated ZVI nanoparticles	Ibrahim et al. (2016)
	Reactive blue 4 (RB4)	Carbon nanotube	
	Alizarin red S (ARS) and Morin		
Pesticides	Dubinin	Carbon nanotube	
	Diuron and dichlobenil		
	Atrazine		
Benzene Derivatives Phenolic Compounds	2,4,6-Trichlorophenol (TCP)	Carbon nanotubes with treatment of HNO3	
	Benzene, toluene, ethylbenzene, and p-xylene	Carbon nanotube with treatment of sodium hypochlorite (NaOCl)	
	1,2-Dichlorobenzene (1,2 DCP)	Graphitized carbon nanotube	
	Chlorophenol	Graphitized carbon incorporated by Ni/Fe Nanoparticles	Zhuang et al. (2021)
Pharmaceuticals	Ciprofloxacin (CPI)	Graphitized (MG), hydroxylated (MH) and carboxylized (MC)	Ibrahim et al. (2016)
	Ibuprofen (IBU)	HNO_3 on carbon nanotube (OMWCNTs)	

(continued)

Table 2 (continued)

Organic /inorganic Contaminants	Target specific contaminant	Nanoparticles used in bioremediation	References
	Tetracycline (TC)	sodium hypochlorite on carbon nanotube	
	Epirubicin (EPI)	Modification of carbon nanotube with HNO3	
Natural organic maters (NOMs)	Humic acid (HA)	Carbon nanotube with modification of HNO3 and H2SO4	
	Fulvic acid (FA)		

tea extracts assisted synthesis of zero-valent iron nanoparticles are responsible for degradation of methylene blue, methylene orange, bromophenol blue and malachite green dyes (Ibrahim et al. 2016; Puthukkara et al. 2021b).

Pesticides

Carbon nanotubes are responsible for degradation of diuron, dichlobenil, atrazine and dubinin. Diuron degradation is influenced by hydrogen bonding. Addition of an oxygen-containing group increases the adsorption of pesticides on carbon nanotubes (Ibrahim et al. 2016).

Benzene Derivatives, Phenolic Compounds

Benzene-containing compounds like 1,2-Dichlorobenzene (1,2 DCP) are degraded at high pH with the help of graphitized carbon nanotubes. Dye degradation requires a low pH, but compounds like benzene require a high pH for degradation. A decrease in adsorption capacity results from more water molecules being formed due to photocatalytic degradation. With the help of HNO3, carbon nanotubes can also be used for the degradation of 2,4,6-Trichlorophenol (TCP). Carbon nanotubes oxidized with sodium hypochlorite (NaOCl) generally degrade compounds such as p-xylene, ethylbenzene, toluene and benzene (Ibrahim et al. 2016).

Pharmaceuticals

The wastewater released by pharmaceutical industries contains several traces of drugs which adversely affect both humans and the environment. A number of drugs in pharmaceutical industry wastewater are epirubicin (EPI), ciprofloxacin (CFX), tetracycline (TC), ibuprofen (IBU). Carbon nanotubes are used to degrade pharmaceutical drugs (Ibrahim et al. 2016) (Table 2).

Table 3 Bioremediation of microbial contamination through nanoparticles

Microbial Contaminants	Target specific contaminant	Nanoparticles used in bioremediation	References
	E. coli	Silver nanoparticles, Ag Nanowire	Yadav and Kumar (2017)
		AgNPs/PU, Ag/CNT/PU sponges, AgNPs polypropylene filters, Polysulfone/AgNPs, AgNW/CNT	Ojha (2020)
		MgO nanoparticles	Ojha (2020)
	Bacillus subtillus	Magnesium nanoparticles	Yadav and Kumar (2017)
	P. aeruginosa,	Magnetic Fe3O4/SiO2,	Dimapilis et al. (2018), Al-Issai et al. (2019), Wang et al. (2019), Ojha (2020)
	Staphylococcus aureus	Silver nanoparticles, ZnO, CuO, Tio2	
	Salmonella typhi	Silver nanoparticle, ZnO, CuO, Tio2	

Natural Organic Matter

For absorption of natural organic matter like Fulvic acid (FA), Humic acid (HA) carbon nanotubes are used with a combination of H_2SO_4 and HNO_3.

4.3 *Microorganism*

Microorganisms play a great role in toxic metal reduction but sometimes microorganisms may lead to contamination of water. Nanoparticles from various syntheses can remove microorganisms' contamination. In most cases, silver nanoparticles are used to kill microorganisms. The fungi mediated silver nanoparticle is found to be effective against bacteria like *S. aureus* and *C. violaceum* (Durán et al. 2007), Table 3 shows Microbial contamination and nanoparticles for removal of it.

5 Recent Research Trends and Advances in Bioremediation

Various industries emit wastewater that contains Microplastics (MPs), which are plastic particles with a size of about 5 mm, and nano plastics, which are plastic particles with a size less than 100 nm. Plastics of this type are either formed by the degradation of larger plastic materials or directly from products in which they are used. In both cases, such plastics have serious health risks. Studies on drinking water treatment plants show more than 400 mg MPs per litre, which is dangerous to human health. Currently, no treatment is available for the complete removal of MPs. Due to its hydrophobic surface and ability to absorb pollutants, MPs may cause problems in other wastewater treatment systems. As a result, it is difficult to evaluate the effectiveness of particular wastewater treatment methods. MPs can be removed at a certain level using activated carbon (AC) infiltration (Jjagwe et al. 2021).

Recently, one interesting strategy for wastewater treatment has been the use of hydrogel-mediated composites for the removal of organic and inorganic pollutants. Hydrogel based solutions have a good adsorbent capacity as compared to conventional adsorbents.

The polymer networks in hydrogel have a large absorption capacity, and they have several better properties like durability, porosity, photostability, and odourlessness. Yi et al. demonstrated the five-cycle reusability of hydrogels formed from graphene oxide, polyvinyl alcohol, and alginate on the methyl orange dye in 20 min. Using two different kinds of polymer of alginate, i.e., alloy site nano-composite beads and calcium alginate show reusability after ten cycles of the cycle (Thakur et al. 2018).

A novel kind of titanate nanocomposite sheet immobilized from silk fibroin has been reported by Magri et al., approximately 75% of Pb2+ can be absorbed on this sheet. During the whole process, even after several rounds of treatment, it does not lose its capacity or show any degradation of the composite material. The selectivity of these immobilized titanate sheets on solid silk fibroin nanocomposite was enhanced by the addition of sodium ions (Magrì et al. 2018).

Today, researchers are making use of surface functionalized silica nanoparticles for water purification. Silanol group on silica increases surface activity of nanoparticles and protects them from leaching. Wang et al. describe the development of silica-based adsorbent models for heavy metals. Study by Di Natalea et al. showed that carbon nanoparticles supported by silica are capable of absorbing heavy metals from wastewater, such as Pb2+, Ni2+ and Cd2+. In certain conditions, such as when the temperature is around 100 0C and the pH is neutral, Ni2+ is removed faster than Cd2+. Other investigations of heavy metal removal by Sheeta et al. using different nanostructures such as silica/graphite oxide composites, graphite oxide, and silica nanoparticles. Composites of silica/graphite oxide in a ratio of 2:3 exhibit the highest efficiency of heavy metals among these three materials. In a recent study, Li et al. developed a new silica nano adsorbent whose surface has a functionalizing component designed specifically to eliminate heavy metals from wastewater. The novel kind of surface modification is made with five kinds of functional groups; these modifications are unique and were initially used for the removal of heavy metals. The silica modified with EDTA as a functionalizing group was able to absorb more Pb than the other four groups. As a method of removing trihalomethanes (THMs) from water by using the sintered process, Ulucan et al. reported that Fe2O3 nanoparticles sintered in zeolite showed a superior level of absorption (Janani et al. 2022).

For removal of Pb^{2+} from aqueous medium two kinds of nano-zero-valent iron were used. One type is iron produced by a reduction method and the other is commercially available iron. This comparative study shows zero valent iron showed more absorption of Pb2 + and in less than 15 min Pb^{2+} was removed from the aqueous system. Elliott et al. synthesized nano-zero-valent iron nanoparticles using sodium borohydride and ferrous sulphate and successfully removed Hexachlorocyclohexane from contaminated water. This nanoparticle formulation can remove almost 95% contaminated Hexachlorocyclohexane with help of a little amount of zero-valent iron nanoparticle (2.2 to 27 $g.L^{-1}$) within 2-day (Puthukkara et al. 2021a).

There are many applications of nanotechnology in bioremediation. It is known that enzyme-based nanoparticles can be used for bioremediation since enzymes act as biocatalysts. The main disadvantage of enzymes is that they are less stable than synthetic catalysts. Since enzymes have a short lifetime, they are not applicable commercially. The stability of enzymes can be increased in many ways. Enzymes play a significant role when attached to the nanoparticle (Rizwan and Ahmed 2018). The advantage of nanoparticles is that they extend the half-life of enzymes by providing extra stability, protecting the enzymes from biotic and mechanical degradation. Enzymes encapsulated within nanoparticles are more stable and can be reused several times, the nanoparticles provide support for the enzymes and protect them from protease attack and therefore biodegradation of enzymes is prevented, ensuring that enzymes last longer. The properties of nanoparticles were tested using complex nanofiber esterase enzymes over a 100-day period. Yadav and Kumar (2017) proved that enzymes continue to function after 100 days.

An enzyme can be separated easily from a product or reactant by combining with iron nanoparticles, which have great magnetic properties. An enzyme can also play an important role in bioremediation, but a combination of enzymes with nanoparticles can also be helpful. A study of this type was conducted by Qiang et al. These experiments used two different enzymes, peroxides and trypsin. As a result of combining these enzymes in core–shell nanoparticles, the activity efficiency, stability, and lifetime of the enzymes was enhanced from an hour to a week. It helps to protect enzymes from oxidation (Rizwan and Ahmed 2018).

It is necessary to recycle waste materials produced by industry into useful products in order to reduce pollution. Due to advances in technology, it is now possible to turn this waste into useful products thanks to excellent technology. In the industry, this concept is more easily applied to the production of biomolecules, adsorbents, biogas, clinker, and biohydrogen from waste. In 2019, Kumar described fermentative bacteria producing biohydrogen in a dark reaction in the presence of nanoparticles (Mandeep and Shukla 2020).

Several researchers are interested in converting industrial wastewater into biohydrogen. There is evidence that Elreedy et al. used mixed kinds of bacteria cultures to produce monometallic, bimetallic and multimetallic nanoparticles for biohydrogen production. The study found that biohydrogen is produced by nanoparticles with multiple combinations of metal ions. As a result, various types of nanoparticles, hydrogenase and dehydrogenase activities increased (Preethi et al. 2019). Gadhe et al., found that biohydrogen production increased in addition to nickel oxide and hematite nanoparticles. The production of biohydrogen is lower in monometallic nanoparticles than in combinations of different metals. Ferredoxin oxidoreductase and hydrogenase enzymes, a mixed metal nanoparticle exhibits 8.83 mmol/g COD (Mandeep and Shuklathe 2020).

In the environment, hydrophobic chemicals such as polycyclic aromatic hydrocarbons (PAHs) tend to persist for long periods of time and affect environmental conditions. Tungittiplakorn et al. develop nanoparticles with modified polyethylene glycol urethane acrylate to deal with this problem. Since polycyclic aromatic hydrocarbons are not soluble in water, they cannot be removed easily by the normal biosorption process; therefore, modified nanoparticles are used. Polymer embedded nanoparticles increase the solubility of hydrophobic chemicals or contaminants (Rizwan and Ahmed 2018).

ZVI can degrade a variety of chlorinated aromatics and polychlorinated biphenyls, as well as aliphatic compounds. During these degradation processes, chlorinated by-products are formed, and these by-products affect the reactivity of iron nanoparticles. This problem will also be solved with advances in nanotechnology. Combination metal therapy plays an important role in chemical degradation. When zero-valent iron nanoparticles combine with metals like Ni, Cu, Zn, and Pd, they show a greater catalytic response than iron nanoparticles alone.

Most commonly, palladium is used as a catalyst for dehalogenation in bioremediation processes using nano-zero-valent iron. By using bimetallic nanoparticles such as Ni/Fe, Xie et al. report on the degradation of polybrominated diphenyl ethers (PBDEs) in the environment. Different types of organic coatings are applied in order to increase the productivity of nanoparticles. These coatings play a variety of roles in activating ZVI molecules. It plays an important role in the modification of the ZVI surface resulting in an increase in the adsorption rate of contaminants on the surface of nanoparticles. Due to redox reactions, electrons get shut down and are responsible for increasing the speed of reaction, so these coatings are also essential to redox reactions. Hydrophobic compounds become more mobile when they are coated with electrolyte organic compounds. Hydrophobic compounds become more mobile when they are coated with electrolyte organic compounds. In the Fe-Pb bimetallic system, contaminants are adsorbent to a greater extent and there are no harmful by-products formed at the end. As a result of the reaction, reactive oxygen species are produced, which are again helpful to dechlorinate the reaction (Koul and Taak 2018b).

The Texas Rice University developed a new kind of nanomaterial called a nano mat, which resembles paper and is used to clean oil spills from ground surfaces as well as water bodies. Numerous petroleum hydrocarbon releases from the oil industry have toxic effects on aquatic environments. The researchers found that thin metal and carbon can trap oil droplets. Multifunctional nanowire structures with a coating of zirconium particles, which have multiple faces, can be used to separate oil from water. A new kind of structure can absorb particles with molecular weights 10 times greater than their original weight (Mohammadi et al. 2020).

6 The Drawback of Nano Bioremediation

In addition to being beneficial, nanoparticle-based solutions are also toxic. A limited amount of literature exists on nanotechnology's drawbacks in bioremediation. Below are some disadvantages of nanotechnology in wastewater treatment. In terms of wastewater treatment, hydrogel has many advantages, but one major disadvantage is the difficulty in recovering it after treatment. After treatment, the substance tends to dissolve and form a solution, so it is difficult to recover it (Thakur et al. 2018).

Advanced nanoparticles such as metallic nanoparticles MNPs accumulate in the environment and are toxic to various ecosystems, including aquatic, terrestrial, and air. Nanoparticles may be accumulated in the environment in different ways; they may enter the environment through the site where they are produced or during their transportation process at the time of their actual application or final disposal. As Nano-engineered materials pass through the aqueous medium, they affect natural processes such as chemical, physical, and also biological processes such as reactions, aggregation, transformation, sedimentation, dissolution, transformation, and sorption (Aguilar-Pérez et al. 2021).

Sharifabadi et al. studied the disinfection of bacteria using modified sodium dodecyl sulphate when it was combined with an ag/cation resin filter system. They found that after treatment there were no bacteria present, but when using a different filter like Ag/ fibre, Ag/sand, Ag/zeolite, and Ag/anion resin show low bacteria removal. This is one of the drawbacks of nanotechnology (Manikandan et al. 2021).

Nanoparticles are rapidly incorporated into animal cells as compared to plant cells because plant cells have a maximal level of external barrier. A nanoparticle present in the soil accumulates in plants through their roots, and in an aqueous medium, heteroaggregation and settlement of the particles may contribute to toxicity. The interaction of nanoparticles with natural organic matter affects the aquatic environment. Various processes are affected by these interactions, including surface transformation, adsorption, dissolution (oxidation and sulfidation), and stabilization/aggregation. According to a study carried out by Cáceres-Vélez et al. on the toxic effect of AgNPs on zebrafish in the presence of humic acid (HA). The result from the experiment shows that if there is more amount of humic acid then AgNPs uptake by zebrafish will reduce. But it doesn't change the effect of AgNPs on zebrafish. The presence of AgNPs in zebrafish bodies leads to toxicity in their body. The main advantage of this mechanism is that it will lower the toxic effects by reducing the uptake of AgNPs in the presence of humic acid. Another experiment was conducted by Selmani et al. to determine the effect of coated selenium nanoparticles on aquatic organisms *Vibrio fischeri* and *Daphnia magna.* The stability of nanoparticles in an aqueous environment depends on the type of medium and surface coating. A comparative study between selenium and selenium coated polyacrylic acid (PAA) shows a toxic effect on 24 and 48 h of exposure. There is another kind of nanoparticle that is most commonly used in bioremediation i.e., iron oxide nanoparticles. Besides their use in bioremediation, it causes toxic effects on the nitrogen cycle (Aguilar-Pérez et al. 2021).

7 Conclusion

We conclude from these chapters that nanotechnology-based solutions for industrial waste are a promising technology for removing pollutants from water bodies. Throughout the last few decades, due to rapid industrialization, new industries have developed day by day. These industries offer immense comfort products for the benefit of humans. Various industries release toxic chemicals that have many side effects. The conventional methods remove toxic chemicals from the environment and provide a toxin-free environment, however if nanotechnology-based solutions are added to conventional methods, speed and effectiveness of the process will be enhanced. In today's world, nanotechnology-based bioremediation solutions can remove various contaminants including organic, inorganic, and biological contaminants. Nanoparticles make this possible due to their unique properties. Because of their easy synthesis, cost-effectiveness, and great functionality, they are widely used. Environmental toxic pollutants can be removed using methods such as adsorption, membrane-based, photocatalysis, disinfection, and redox reaction. Each of these methods has advantages and disadvantages.

References

Abdelbasir SM, Shalan AE (2019) An overview of nanomaterials for industrial wastewater treatment. Korean J Chem Eng 36(8):1209–1225. https://doi.org/10.1007/s11814-019-0306-y

Aguilar-Pérez KM et al (2021) Nanoadsorbents in focus for the remediation of environmentally-related contaminants with rising toxicity concerns. Sci the Total Environ. Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2021b.146465

Ali AEI et al (2011) Pharmacologyonline 1:710–720

Ali I, Gupta VK (2007) Advances in water treatment by adsorption technology. Nat Protoc 1(6):2661–2667. https://doi.org/10.1038/nprot.2006.370

Al-Issai L et al (2019) Use of nanoparticles for the disinfection of desalinated water. Water (switzerland) 11(3):1–20. https://doi.org/10.3390/w11030559

Alshemmari H (2021) An overview of persistent organic pollutants along with the coastal environment of Kuwait. Open Chem 19(1):149–156. https://doi.org/10.1515/chem-2021-0198

Annachhatre AP, Gheewala SH (1996) Biodegradation of chlorinated phenolic compounds. Biotechnol Adv 14(1):35–56. https://doi.org/10.1016/0734-9750(96)00002-X

Assi MA et al (2016) The detrimental effects of lead on human and animal health. Veterinary World 9(6). https://doi.org/10.14202/vetworld.2016.660-671

Berekaa MM (2016) Nanotechnology in Wastewater Treatment; Influence of Nanomaterials on Microbial Systems. Int J Curr Microbiol App Sci 5(1):713–726. https://doi.org/10.20546/ijcmas.2016.501.072

Bernard A (2008) Cadmium & its adverse effects on human health. Indian J Med Res

Bharagava RN, Saxena G, Mulla SI (2020) Introduction to industrial wastes containing organic and inorganic pollutants and bioremediation approaches for environmental management. In: Bioremediation of industrial waste for environmental safety. Springer Singapore, pp 1–18. https://doi.org/10.1007/978-981-13-1891-7_1

Dabhane H et al (2021) Phytogenic synthesis of gold nanoparticles and applications for removal of methylene blue dye: A review. Environ Chem Ecotoxicol 3:160–171. https://doi.org/10.1016/j.enceco.2021.04.002

Das P et al (2018) Madhuca longifolia plant-mediated green synthesis of cupric oxide nanoparticles: A promising environmentally sustainable material for wastewater treatment and efficient antibacterial agent. J Photochem Photobiol B 189:66–73. https://doi.org/10.1016/j.jphotobiol.2018.09.023

Dimapilis EAS et al (2018) Zinc oxide nanoparticles for water disinfection. Sustain Environ Res 28(2):47–56. https://doi.org/10.1016/j.serj.2017.10.001

Division S (2019) Environmental science: nano redox chemistry of CeO 2 Nanoparticles in aquatic systems containing Cr (VI)(aq) and Fe 2+ ions environmental science: nano environmental significance : redox-active CeO 2 NPs are used in many industrial applications. O. Environ Sci: Nano [Preprint], (Vi)

Durán N et al (2007) Antibacterial effect of silver nanoparticles produced by fungal process on textile fabrics and their effluent treatment. J Biomed Nanotechnol 3(2):203–208. https://doi.org/10.1166/jbn.2007.022

El-Batal AI et al (2020) Penicillium chrysogenum-Mediated Mycogenic synthesis of copper oxide nanoparticles using gamma rays for in vitro antimicrobial activity against some plant pathogens. J Cluster Sci 31(1):79–90. https://doi.org/10.1007/s10876-019-01619-3

Gahlawat G, Choudhury AR (2019 A review on the biosynthesis of metal and metal salt nanoparticles by microbes. RSC advances. Royal Soc Chem, pp 12944–12967. https://doi.org/10.1039/c8ra10483b

Hashem EA (2014) Nanotechnology in water treatment, case study: Egypt. J Econ Dev Studies 2(3):244–259. https://doi.org/10.15640/jeds.v2n3a18

He L et al (2015) Contamination and remediation of phthalic acid esters in agricultural soils in China: a review. Agronomy Sustain Dev, 519–534. https://doi.org/10.1007/s13593-014-0270-1

Husein DZ, Hassanien R, Al-Hakkani MF (2019) Green-synthesized copper nano-adsorbent for the removal of pharmaceutical pollutants from real wastewater samples. Heliyon 5(8):e02339. https://doi.org/10.1016/j.heliyon.2019.e02339

Hussain A et al (2016) Exploited application of sulfate-reducing bacteria for concomitant treatment of metallic and non-metallic wastes: a mini review. 3 Biotech 6(2). https://doi.org/10.1007/s13205-016-0437-3

Ibrahim RK et al (2016) Environmental application of nanotechnology: air, soil, and water. Environ Sci Pollut Res. Springer, pp 13754–13788. https://doi.org/10.1007/s11356-016-6457-z

Iravani S (2014) Bacteria in nanoparticle synthesis: current status and future prospects. Int Scholarly Res Notices 2014:1–18. https://doi.org/10.1155/2014/359316

Janani R et al (2022) Advancements in heavy metals removal from effluents employing nano-adsorbents: way towards cleaner production. Environ Res, 203.https://doi.org/10.1016/j.envres.2021.111815

Jjagwe J et al (2021) Synthesis and application of granular activated carbon from biomass waste materials for water treatment: a review. J Bioresources Bioproducts. KeAi Communications Co., pp 292–322. https://doi.org/10.1016/j.jobab.2021.03.003

Kiruba Daniel SCG et al (2014) Multifunctional silver, copper and zero valent iron metallic nanoparticles for wastewater treatment. In: Application of nanotechnology in water research, pp 435–457. https://doi.org/10.1002/9781118939314.ch15

Koul B, Taak P (2018a) Nanobioremediation. In: Biotechnological strategies for effective remediation of polluted soils. Springer Singapore, pp 197–220. https://doi.org/10.1007/978-981-13-2420-8_8

Koul B, Taak P (2018b) Nanobioremediation. In: Biotechnological strategies for effective remediation of polluted soils. Springer Singapore, pp 197–220. https://doi.org/10.1007/978-981-13-2420-8_8

Li X et al (2011) Biosynthesis of nanoparticles by microorganisms and their applications. J Nanomater. https://doi.org/10.1155/2011/270974

Manikandan S et al (2021) Emerging nano-structured innovative materials as adsorbents in wastewater treatment. Bioresource Technol 320. Elsevier Ltd, Jan. 01, 2021. https://doi.org/10.1016/j.biortech.2020.124394

Magrì D et al (2018) Titanate Fibroin nanocomposites: a novel approach for the removal of heavy-metal Ions from water. ACS Appl Mater Interfaces 10(1):651–659. https://doi.org/10.1021/acsami.7b15440

Mandeep, Shukla P (2020) Microbial nanotechnology for bioremediation of industrial wastewater. Front Microbiol. Frontiers Media S.A. https://doi.org/10.3389/fmicb.2020.590631

Mohammadi L et al (2020) Petroleum hydrocarbon removal fromwastewaters: A reviewMohammadi, Leili, Abbas Rahdar, Edris Bazrafshan, Hamid Dahmardeh, Md Abu Bin Hasan Susan, and George Z. Kyzas. 2020. 'Petroleum Hydrocarbon Removal Fromwastewaters: A Review.' Processes, 1–34.," Processes, 8, p 447

Mourdikoudis S, Pallares RM, Thanh NTK (2018) Characterization techniques for nanoparticles: comparison and complementarity upon studying nanoparticle properties, Nanoscale. Royal Soc Chem, pp 12871–12934. https://doi.org/10.1039/c8nr02278j

Munisamy P (no date) Phytochemical analysis and green synthesis of silver nanoparticles by Kariveppillai fruits extract-biological activity study phytochemistry view project. Available at www.tnsroindia.org.in.

Shah MP (2020a) Microbial bioremediation & biodegradation. Springer

Ojha A (2020) Nanomaterials for removal of waterborne pathogens. Elsevier, Waterborne Pathogens. https://doi.org/10.1016/b978-0-12-818783-8.00019-0

Okhovat N, Hashemi M, Golpayegani AA (2015) Photocatalytic decomposition of Metronidazolein aqueous solutions using titanium dioxide nanoparticles. J Mater Environ Sci 6(3):792–799

Pandey G (2018) Prospects of Nanobioremediation in environmental cleanup. Orient J Chem 34(6):2838–2850. https://doi.org/10.13005/ojc/340622

Shah MP (2021a) Removal of refractory pollutants from wastewater treatment plants. CRC Press

Preethi et al (2019) Biohydrogen production from industrial wastewater: an overview. Bioresource Technol Reports, p 100287. https://doi.org/10.1016/j.biteb.2019.100287

Puthukkara PAR, Jose TS, lal SD (2021a) Plant mediated synthesis of zero-valent iron nanoparticles and its application in water treatment. J Environ Chem Eng. Elsevier, p 104569. https://doi.org/10.1016/j.jece.2020.104569

Puthukkara PAR, Jose TS, lal SD (2021b) Plant mediated synthesis of zero valent iron nanoparticles and its application in water treatment. J Environ Chem Eng. Elsevier Ltd. https://doi.org/10.1016/j.jece.2020.104569

Shah MP (2021b) Removal of emerging contaminants through microbial processes. Springer

R Ali H (2017) Applications of bio-waste materials as green synthesis of nanoparticles and water purification. Adv Mater 6(5):85.https://doi.org/10.11648/j.am.20170605.16

Rizwan M, Ahmed MU (2018) Nanobioremediation: Ecofriendly application of nanomaterials. In: Martínez LMT et al. (eds), Springer International Publishing AG, part of S.N. 2018 and, H. of E. (eds) handbook of ecomaterials. Springer International Publishing, pp 1–14. https://doi.org/10.1007/978-3-319-48281-1_97-2

Rizwan Md et al (2014) Eco Friendly application of nanomaterials: Nanobioremediation. J Nanoparticles, pp 1–7.https://doi.org/10.1155/2014/431787

Roy A (2014a) Nanotechnology in industrial wastewater treatment. Water Intell Online 13:220. https://doi.org/10.2166/9781780406886

Roy A (2014b) Nanotechnology in industrial wastewater treatment. Water Intell Online. https://doi.org/10.2166/9781780406886

Rumschlag SL et al (2020) Consistent effects of pesticides on community structure and ecosystem function in freshwater systems. Nat Commun 11(1):1–9. https://doi.org/10.1038/s41467-020-20192-2

Sastry M et al (2003) Biosynthesis of metal nanoparticles using fungi and actinomycete. CurrentSci, pp 162–170. Available at https://www.researchgate.net/publication/228550063

Shah MP (2020b) Microbial bioremediation & biodegradation, microbial bioremediation & biodegradation. Springer Singaporehttps://doi.org/10.1007/978-981-15-1812-6

Sherry Davis A, Prakash P, Thamaraiselvi K (2017) Nanobioremediation technologies for sustainable environment. Environmental science and engineering (Subseries: Environmental Science), (9783319484389), pp 13–33. https://doi.org/10.1007/978-3-319-48439-6_2

Singh E, Osmani RAM, Banerjee R (2020) Nanobioremediation: an emerging approach for a cleaner environment. In Microbial bioremediation & biodegradation, pp 309–363. https://doi.org/10.1007/978-981-15-1812-6_12

Singh PK, Singh RL (2017) Bio-removal of azo dyes: a review. Int J Appl Sci Biotechnol 5(2):108–126. https://doi.org/10.3126/ijasbt.v5i2.16881

Tandon PK, Singh SB (2016) Redox processes in water remediation. Environ Chem Lett 14(1):15–25. https://doi.org/10.1007/s10311-015-0540-4

Thakur S et al (2018) Recent progress in sodium alginate based sustainable hydrogels for environmental applications. J Clean Prod 198:143–159. https://doi.org/10.1016/j.jclepro.2018.06.259

Vo TT et al (2019) Biosynthesis of silver and gold nanoparticles using aqueous extract from crinum latifolium leaf and their applications forward antibacterial effect and wastewater treatment. J Nanomaterials.https://doi.org/10.1155/2019/8385935

Wang X et al (2019) Mesoporous silica-protected silver nanoparticle disinfectant with controlled Ag+ ion release, efficient magnetic separation, and effective antibacterial activity. Nanoscale Adv 1(2):840–848. https://doi.org/10.1039/c8na00275d

Yadav KK et al (2017) A review of nanobioremediation technologies for environmental cleanup: a novel biological approach. J Mater Environ Sci 8(2):740–757

Yadav KK, Kumar V (2017) A review of Nanobioremediation technologies for environmental cleanup: a novel biological approach micro plastic in aquatic biota view project testbook for students View project. JMES. Available at http://www.jmaterenvironsci.com/

Zekić E, Vuković Ž, Halkijević I (2018) Application of nanotechnology in wastewater treatment. Gradjevinar 70(4):315–323. https://doi.org/10.14256/JCE.2165.2017

Zhuang M et al (2021) Carbothermal synthesis of ni/fe bimetallic nanoparticles embedded into graphitized carbon for efficient removal of chlorophenol. Nanomaterials 11(6). https://doi.org/10.3390/nano11061417