Environ Monit Assess (2022) 194:730
https://doi.org/10.1007/s10661-022-10315-1

Biosynthesis and chemical composition of nanomaterials in agricultural soil bioremediation: a review

Rasel Rana · Jannatul Ferdous · Mizanur Rahman · Fahida Rahman · Amdadul Huq · Yousof Ali · Nazmul Huda · Muntaha Binte Mukhles · Meherab Hossain Rafi

Received: 3 May 2022 / Accepted: 25 July 2022 /

Abstract Nanomaterials (NMs) are currently being used in agricultural soils as part of a new bioremediation (BR) process. In this study, we reviewed the biosynthesis of NMs, as well as their chemical composition and prospective strategies for helpful and sustainable agricultural soil bioremediation (BR). Different types of NMs, such as nanoparticles, nanocomposites, nanocrystals, nano-powders, and nanotubes, are used in agricultural soil reclamation, and they reflect the toxicity of NMs to microorganisms. Plants *(Sargassum muticum, Dodonaea viscose, Aloe Vera, Rosemarinus officinalis, Azadirachta indica,* Green tea, and so on) and microorganisms (*Escherichia coli, Shewanella oneidensis, Pleurotus* sp., *Klebsiella oxytoca, Aspergillus clavatus*, and so on) are the primary sources for the biosynthesis of NMs. By using the BR process, microorganisms, such as bacteria and plants, can immobilize metals and change both inorganic and organic contaminants in the soil. Combining NMs with bioremediation techniques for agricultural soil remediation will be a valuable long-term solution.

Keywords Agricultural soil · Bioremediation (BR) · Biosynthesis · Nanomaterials (NMs) · Nanoparticles · Nanotechnology

Introduction

Bioremediation (BR) is a method that converts pollutants from soil, water, and different types of sources by using microorganisms (Huda et al., 2021). Microorganisms, such as bacteria, fungi, algae, protozoans, and others, are frequently used to degrade organic matter in a polluted environment (Mandal et al., 2021; Rizwan et al., 2014). Microorganisms are used with oxygen gas, fertilizer, and other factors during in BR process that helps their rapid growth as they remove organic pollutants (Pandey, 2018). These microbes, which are used specifically in genetic engineering and other molecular biological techniques, can be applied to break down pollutants and consume toxic chemical agents (Balciunas et al., 2013; Enamala et al., 2019; Rizwan et al., 2014). The main advantages of the BR method are highly efficient for example easily selects specific metals, easily

R. Rana · J. Ferdous · M. Rahman (✉) · F. Rahman · N. Huda · M. B. Mukhles · M. H. Rafi
Department of Biotechnology and Genetic Engineering, Faculty of Biological Science, Islamic University, Kushtia 7003, Bangladesh
e-mail: mmrahmanbtg79@hotmail.com

A. Huq
Department of Food and Nutrition, College of Biotechnology and Natural Resources, Chung-Ang University, Gyeonggi-do, Anseong-si 17546, Republic of Korea

Y. Ali
Department of Physiology and Pharmacology, Hotchkiss Brain Institute, and Alberta Children's Hospital Research Institute, Cumming School of Medicine, University of Calgary, Calgary, AB T2N 4N1, Canada

minimizes chemical and biological sludge, as well as has no requirements for supplementary nutrition for recovery of heavy metals (Rizwan et al., 2014). Sometimes, the BR process may happen naturally as defined in an innate diminution or inherent BR (Kungwani et al., 2022). Different types of technologies such as bio-stimulation, hemofiltration, land farming, composting, phytoremediation, bioreactor, and bioventing are very common processes of BR (Huda et al., 2021; Thomassin-Lacroix et al., 2002). The in situ BR method removes the harmful and poisonous chemicals in the area (Karlapudi et al., 2018). The ex situ BR method needs to treat the polluted substances or poisonous materials by digging in the soil (Rizwan et al., 2014).

Nano-bioremediation (NBR) is a method for disposing of detrimental pollutants into secure molecules by treating the different types of microorganisms in connection with NMs that are smaller than100 nm (Mallikarjunaiah et al., 2020). Several NMs—Zn, Cu, Au, and Ag— are synthesized with a lot of microorganisms and plants that are accessible in the literature and useful in breaking down harmful contaminants (Gupta et al., 2020). Scientists have extensively investigated the different combinations of synthesized NMs. This combined process involves a wide range of potential applications with lower costs and the least impact on our environment when mediating contaminants in wastewater, groundwater, and sediments contaminated with heavy metals as either inorganic or organic compounds in the soil (Vázquez-Núñez et al., 2020). NMs have a special ability to remove toxic elements and develop the microbial action of the defined toxic item (Pandey, 2018). Agricultural soil remediation seems like a useful approach for dealing with pollution control by using biosynthetic NMs. The goal of this review is to provide a general overview of the biosynthesis of NMs from plants and microorganisms and the chemical compositions of NMs. This review article is a summary of the latest enhancements in the techniques of agricultural soil remediation for the various contaminated areas of our environment. The potential impact of using NMs on environmental pollution, especially in agricultural soil, is also presented and discussed.

NMs and nanotechnology

NMs can be applied in almost every field of science—agriculture, food, medicine, engineering, space, cosmetics, defense, automobiles, textiles, and the environment (Singh et al., 2020). With great achievements in the field of NMs and nanotechnology, their importance in supplying advanced and efficient keys to ecological contexts is becoming gradually more significant (Chauhan et al., 2020). NMs have gained much attention from researchers throughout the world in the different sectors of the sciences that are very closely related to the environment, specifically BR (Chauhan et al., 2020). The surface activity of NMs can be customized to develop their selectivity for sample removal (Chauhan et al., 2020; Zamborini et al., 2012; Huang et al., 2009). Different types of NMs with their chemical presentations, structures, and examples are described in Table 1.

Nanoparticles, such as nano scale-zero-valent iron (nZVI), are metals that act as a reducing agent that transfers their electrons from iron and degrades a wide range of contaminants (Visentin et al., 2021). Nanocomposites are composed of different types of flexible and non-flexible NMs. Nanocrystals are composed of crystalline fragments of at least 1000 nm. For example, zinc sulfide is a nanocrystal that contains two different crystalline components: wurtzite and zinc-blende (Torres-Martinez et al., 2001). Nanopowder forms a massive number of atoms that bond to one another with a range from 1 to 100 nm. A nanosponge is a kind of nanomaterial that is a highly cross-linked carbon-containing polymer. These are tiny sponges porous in structure (Baglieri et al., 2013). Nanotube has, as so named, a tube structure, and a carbon nanotube (CNT) is a special carbon atom grapheme.

NMs consist of different types of chemical and physical materials, and their costs are high (Sebastian et al., 2014). The usage of harmful chemicals and the production of the poisonous secondary products have opened the way for the creation of biogenic NMs. Many researchers have described the different types of NMs, including iron (Fe), silver, zinc, copper, and gold, by using different types of microorganisms, such as bacteria, fungi, algae, yeasts, actinomycetes, and plant extracts (Das et al., 2018; Huq et al., 2022; Moholkar et al., 2020).

Using different biological factors in the biosynthesis of NMs is a growing research topic in green nanotechnology (Ganguly et al., 2018). Nowadays, many scientists have paid attention to the rise of nanotechnology as a plainer and more robust instrument. Nanotechnology has been applied to removing toxic pollutants that exist in small amounts in soil,

Table 1 List of NMs with chemical composition with structure

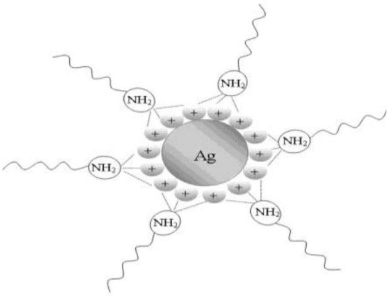
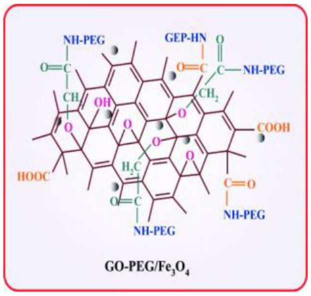
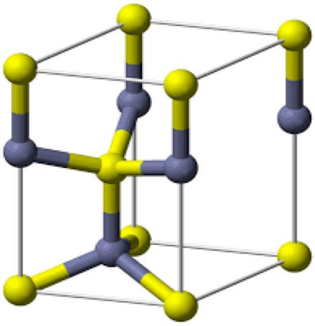
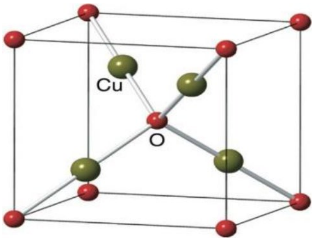
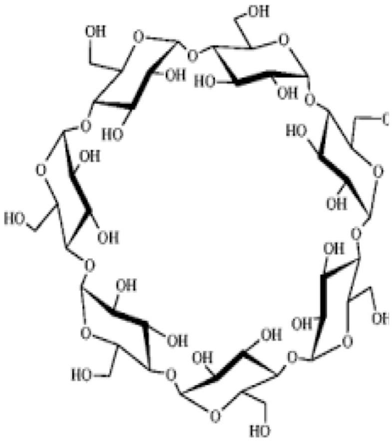
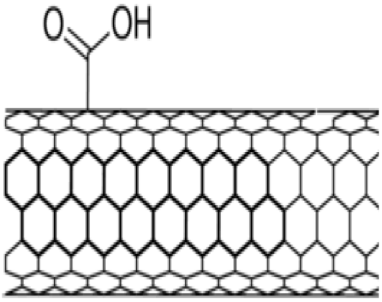
NMs	Chemical presentation	Example	Structure	References
Nanoparticles	Nano scale-zero-valent iron (nZVI), here iron is metal and acts as a reducing agent, ZVI transferred the electron from iron. They are capable to degrade a wide range of contaminants.	Fe, Ti, Mn, Ag, Au.		Kim et al., 2012
Nanocomposite	Various multiple NMS were arrested inside amass materials. They are composed of a flexible and non-flexible NMS, two non-flexible or two flexible NMS.	Polyethylene oxide, Polyethyleneimine.		Lui et al., 2018
Nanocrystal	Nanocrystal is composed of a crystalline fragment with leastwise 1000 nanometers. Zinc sulfide is a Nanocrystal that contains two different crystalline components.1. Wurtzite 2. Zincblende.	ZnS (zinc sulfide), Al_{203}		Torres et al., 2001
Nano powders	It is a powder material that formed a massive number of atoms that bind one another with a range from 1 nm to 100 nm.	Iron oxide Fe2o3, Fe_{304}.		Kos et al., 2014

Table 1 (Continued)

NMs	Chemical presentation	Example	Structure	References
Nano sponge	One kind of nanomaterial is a highly cross-linked carbon-containing polymer. They are tiny sponges porous in structure.	Cyclodextrin, Temozolamide, pactixer.		Baglieri et al., 2013
Nanotubes	It is a Nano scale/ microscopic tube that looks like a tube structure. Carbon nanotube (CNT) is a special carbon atom+ grapheme.	Single-walled CNT, Multi-walled CNT.		Mechrez et al., 2014

air, and water (Das et al., 2015; O'Carroll et al., 2013; Dhillon et al., 2012). Nanotechnology also acts as a catalyst that reduces the number of objects used in the manufacturing procedure and reduces the production of detrimental wastes (Chauhan et al., 2020). Nanotechnology has given innovative scope to ecological cleanups, and it is an efficient substitute for commercial remediation as it facilitates both chemical reductions and rapid catalysis to reduce the contaminants of concern (Yaqoob et al., 2020). Nanotechnology has been used for dealing with the BR of uranium contamination, solid wastes, hydrocarbons, wastewater remediation, heavy metal contamination, soil pollution, and groundwater pollution (Alazaiza et al., 2021; Ojuederie & Babalola, 2017; Nematollahzadeh et al., 2015).

Principles and concepts of NBR

NBR can reduce the total expenditures on cleaning up major pollution with decreased clean up time (Enamala et al., 2019). The fundamental theory of NBR is termed as the deterioration of organic pollutants via nano-catalysts as a medium that permits them to enter deep inside the pollutants and deal with them carefully without influencing the nearby assistance of numerous microbes (Moholkar et al., 2020). These microbes appear in all places in the world and are struggling to live with the people on the earth. On the other hand, these microbes have different types of benefits like altering heavy metals into nonpoisonous forms, such as carbon dioxide and water, with the help of the mineralization of the organic pollutants. Even these can lead to various metabolic intermediates that can be used as metabolites for their development and growth (Enamala et al., 2019; Thakur et al., 2018). Besides, microbes protect their cell walls from the poisonous materials by producing degradable enzymes (Vardhan et al., 2019). When pollutants are consumed by microbes, they increase their unique surrounding membrane which helps them resist the entry of foreign materials into their cells (Murínová & Dercová, 2014). For a successful remediation method, researchers should consider the improvements of microorganisms mechanisms, such as development, growth, and movements in polluted sites (Enamala et al., 2019). The main idea about the NBR is that it describes the size of the NMs because their very small particles permit them to enter the polluted areas with different microbes, such as fungi, bacteria, and others.

Many scientists have included this study as part of their research because NMs can generate better outcomes when compared with the micro materials found in polluted areas (Enamala et al., 2019). The cleanup method is considerably delayed when compared to the usual BR technology. Some of the nano-based materials used for dealing with such polluted areas are nanocomposites, nanocrystals, nano-powders, nanotubes, and others. These NMs can be treated to immobilize the cells of microbes that then break down or be used in the recovery of precise chemicals depending upon the researcher's interest (Enamala et al., 2019).

The science of NBR and biosynthesis of NMs

NBR is the main adaptable method for a strong environmental cleanup. The removal of environmental pollutants (for example, organic and inorganic contaminants and heavy metals) from polluted areas using NMs produced by microorganisms (for example, bacteria, and fungi) or plants with the help of nanotechnology is termed NBR (Chauhan et al., 2020; Ramezani et al., 2021; Vázquez-Núñez et al., 2020). NMs seem like an excellent substitute for existing techniques because of their price value, high competence, and friendliness to the environment. Iron (Fe) is regarded to be the first nanomaterial (NM) to be utilized for environmental cleanup (Chauhan et al., 2020). Several optimistic iron-based methods are accessible for the cleaning of polluted soil or for groundwater remediation (Chauhan et al., 2020). Zinc (Zn) as NMs have been widely used and investigated by scientists around the world because of its outstanding capability to break down organic dyes (Banerjee et al., 2021). As a semiconductor photocatalyst, Zn as an NM can contribute to the breaking down of a large variety of compounds from different types of dyes such as phenols and pharmaceutical medicines (Chauhan et al., 2020). NMs like as silver (Ag) and gold (Au) have an enormous application in a variety of areas, with the most significant application being the breakdown of organic dyes (Lu & Astruc, 2020). Copper (Cu) NM has also exhibited excellent results in breaking down organic dyes (Kim et al., 2018; Pandey, 2018; Shahwan et al., 2011).

The biosynthesis of NMs from plants and microorganisms and the remediation of different contaminants by NMs are shown in Table 2. NM such as nano iron is synthesized from plants *(Sargassum muticum, Dodonaea viscose, Aloe vera, Azadirachta indica, Cartaya papaya*, Green tea, etc.*)* and microorganisms (*Escherichia coli, Shewanella oneidensis, Pleurotus* sp., *Klebsiella oxytoca, Aspergillus clavatus*, etc.). *Rubus glaucus, Ricinus communis, Nerium oleander, Calotropis gigantean, Nerium oleander,* etc. are the plant sources for the biosynthesis of nano copper and the microorganism sources are *Streptomyces* sp., *Fusarium oxysporum, Penicilium citrinum, Hypocrea lixii,* etc.) (Table 2). Nanosilver is synthesized from *Artemisia nilagirica, Nerium oleander, Sinapis arvensis,* and other plant sources described in Table 2. *Streptomyces naganishii, Brevibacterium casei, Trichoderma reesei,* etc. are the plant sources for the biosynthesis of nanosilver. Nano zinc and gold are also synthesized from different plants and microorganisms (see details in Table 2). Yeast and fungi can also be utilized for the biosynthesis of NMs (Alghuthaymi et al., 2015). Whenever there is a need to produce huge quantities of NMs, fungi can be utilized as a result of their characteristic feature of having huge amounts of proteins (Pandey, 2018). In the biogenic manufacturing of metal NMs by a fungus, several decreasing enzymes with their catalytic results are made that lessen salts to their equivalent metallic solid NMs (Singh et al., 2020). This catalytic outcome is the main weakness of the microbial synthesis of NMs and requires making corrections for the wider application of this technique.

Table 2 Biosynthesis of NMs from plants and microorganisms with the remediation of different contaminants

NMs used	NMs source from plant	NMs source from microorganisms	Pollutant removed	References
Iron (Fe)	*Sargassum muticum*	*E. coli*	Atrazine, Alachlor	Mahdavi et al. (2013), Arčon et al. (2012), Bezbaruah et al. (2009)
	Dodonaea viscose	*Shewanella oneidensis*	Trichloroethylene	Phumying et al. (2013a, b), Narayanan and Sakthivel (2011), Smuleac et al. (2011)
	Aloe vera	*Pleurotus* sp.	Total petroleum hydrocarbons	Murgueitio et al. (2018), Pandey (2018), Kumar et al. (2011)
	Azadirachta indica	*Klebsiella oxytoca*	Chlorinated ethanes, Dissolved sulfides	Chaung et al. (2014), Binupriya et al. (2010), Song et al. (2005)
	Rosemarinus officinalis	*Aspergillus clavatus*	As(III), Cr(VI)	Pandey (2018), Saravanan and Nanda (2010), Pradeep (2009)
	Sorghum bran	*Chaetomium globosum*	Brominated methanes, Perchlorate	Pandey (2018), Lim et al. (2007)
	Eucalyptus tereticornis		2,4-dichlorophenol, Polychlorinated biphenyls (PCBs)	Pandey (2018), Guo et al. (2017), Choi et al. (2008)
	Cartaya papaya		Pentachlorophenol, Dibenzo-p-dioxins, and furans	Kim et al. (2008), Kim et al. (2012)
	Green tea		Arsenic(V), Copper(II), Pb(II), Hg(II), Cr(VI) Cd(II), Ni(II), Uranium, Cd2 +, Ni + 2, Co + 2	Boparai et al. (2013), Hooshyar et al. (2013), Kumar et al. (2013), Li et al. (2013), Fan et al. (2012), Ambashta and Sillanpää (2010), Mahdavian and Mirrahimi (2010), Pradeep (2009)
Copper (Cu)	*Rubus glaucus*	Penicillium aurantiogriseum	Chlorobenzene	Hasanin et al. (2021), Abboud et al. (2014), Lee et al. (2011)
	Ricinus communis	*Shewanella oneidensis*	Pyrene	Yaqub et al. (2020), Kim et al. (2018), Chang et al. (2009)
	Tabernaemontana divaricate	*Penicillium waksmanii*	Cr(VI)	Pandey (2018), Cutting et al. (2010)
	Punica granatum	*Hypocrea lixii*	Cationic and anionic Dyes	Murthy et al. (2018), Pandey (2018), Shahwan et al. (2011)
	Green tea	*Pseudomonas* sp., *Serratia* sp.	Dichloroethane	Kim et al. (2018), Wang et al. (2014), Wei et al. (2012)
	Ocimumten uiflorum	*Penicilium citrinum*	Cu(II), Pb(II)	Pandey (2018), Mahdavian and Mirrahimi (2010)
	Ficus religiosa	*Streptomyces* sp.	Nitrate	Pandey (2018), Sankar et al. (2014)
	Nerium oleander	*Sternum hirsutum*	Several metal transition elements	Enamala et al. (2019), Pandey (2018)
	Carica papaya	*Pseudomonas stutzeri*	Dichloromethane	Pandey (2018), Sankar et al. (2014), Huang et al. (2012)
	Gloriosa superba	*Fusarium oxysporum*	Methylene blue	Shende et al. (2015), Sinha and Ahmaruzzaman (2015)
	Calotropis gigantean		Methyl orange	Sharma et al. (2015)

Table 2 (continued)

NMs used	NMs source from plant	NMs source from microorganisms	Pollutant removed	References
Silver (Ag)	*Sinapis arvensis*	*Staphylococcus aureus*	Organic dyes	Moholkar et al. (2020), Pandey (2018)
	Lantana camara	*Trichoderma reesei*	Textile effluent	Corso et al. (2009), Nanda et al. (2009)
	Trigonella foenumgraecum	*Brevibacterium casei*	Coomassie brilliant blue G-250	Pandey (2018), Arunachalam et al. (2012)
	Artemisia nilagirica	*Streptomyces* sp.	Methylene blue	Rasheed et al. (2017), Teng et al. (2015) Morones et al. (2005)
	Butea monosperma	*Streptomyces naganishii*	Congo red	Kumar et al. (2012)
	Nerium oleander	*Neurospora crassa*	*p-nitrophenol*	Gangula et al. (2011)
Zinc (Zn)	*Ixora coccinea*	*Lactobacillus*	Formaldehyde	Lee et al. (2008)
	Aloe vera	*Streptomyces* sp.	Resorcinol	Raliya and Tarafdar (2014), Phumying et al. (2013a, b), Pardeshi et al. (2009)
	Trifolium pretense	*Candida albicans*	Cd(II)	Dobrucka and Długaszewska (2016)
	Limonia acidissima		Congo red and Benzopurpurine 4B	Pandey (2018)
	Plectranthusam boinicus		Methylene blue, Malachite green	Pandey (2018) Khezami et al. (2016), Srivastava et al. (2013)
	Nyctanthesarbor-tristis		Organic dyes, Direct red 23	Pandey (2018), Sanna et al. (2016), Kumar et al. (2014)
	Parthenium hysterophorus		Phenol, Brown CGG dye	Yuvak kumar et al. (2015), Kruefu et al. (2012)
	Pongamia pinnata		Fuchsine, Rhodamine B	Pandey (2018), Zhou et al. (2009)
Gold (Au)	*Anacardium occidentale*	*Streptomyces viridogens*	Methylene blue	Pandey (2018), Gupta et al. (2010), Gupta et al. (2010)
	Zingiber officinale	*Penicillium brevicompactum*	p-Nitrophenol	Kanchi et al. (2018), Mishra et al. (2011), Huang et al. (2009)
	Abelmoschus esculentus	*Klebsiella pneumonia*	Tertiary dye effluent (Methyl orange, Acid red, Acid orange)	Pandey (2018), Sathishkumar et al. (2013)

Engineered polymeric NMs for soil remediation

Some pollutants are found in the environment, for example, polynuclear aromatic hydrocarbons (PAHs) that are fixed to the soil. Therefore, it is very difficult to remove these pollutants from the soil (Patel et al., 2020; Loick et al., 2009). Recently, researchers have synthesized a few particles identified as amphiphilic polyurethane (APU) for the remediation of the soil polluted with PAHs (Mazarji et al., 2021; Rahman et al., 2022). The APU consists of polyurethane acrylate ionomers (PAIs) or polyethylene glycol. The colloidal dimension of APU is 17 – 97 nm by dynamic light scattering(Rizwan et al., 2014). APU can increase PAH's desorption, stability, and independence in the aqueous stage (Johari et al., 2010). APU elements must be engineered to attain ideal features with a hydrophobic center region (Javaid et al., 2020). These elements also offer a high attraction for phenanthrene and hydrophilic surfaces, which then improves the elements' mobility in the soil (Javaid et al., 2020). The affinity of APU elements may be controlled for pollutants by altering the dimension of the hydrophobic segment, for example, phenanthrene (Rizwan et al., 2014). The mobility of colloidal APU suspensions is controlled in the soil by the charge density. The capability to control particles features offers the potential to produce diverse NPS optimized for various pollutants and soil conditions (Rizwan et al., 2014).

An engineered iron NM solution is nonpoisonous, highly reactive, and very efficient, and it can quickly take away the soil pollutants (Reddy et al., 2016). This engineered iron NM is efficiently utilized for the removal of chlorinated hydrocarbons and different heavy metals present in the soil. First, the iron NM is inserted into the soil. Second, it reacts with the pollutants, and then it is absorbed into them as shown in Fig. 1. This method can also be applied to remediate the industrial pollutants from the agricultural soil (Enamala et al., 2019).

Challenges with NMs

While NMs have shown hopeful outcomes in removing polluted areas, there are some troubles related to their decreasing reactivity after a defined time, their conduction, and their outcomes on bacteria, fungi, and other microorganisms (Pandey, 2018). Iron (Fe) NMs have a reduction in their reactivity stage (after a defined time) and an obstructive outcome in the soil from blocking the holes in the soil thus confining the route of liquids. It has also been shown that a stabilizer (for example, lactate) may be treated to develop the dynamism of Fe NMs (Karimi & Mohseni Fard, 2017). A variety of guidelines under distinct situations have been carried out on the outcome of NMs on microorganisms. Among them, some of the guidelines have shown inhibitory results on microbes similar to *Escherichia coli* and *Staphylococcus aureus* (Pandey, 2018). Other studies have demonstrated the exciting outcome of NMs as electron contributors on microbes, for example, methanogens and bacteria (Chauhan et al., 2020).

Soil microbes are enormously significant to the normal series of nutrients in the environment, and they can break down the organic pollutants or diminish and arrest heavy metals (China et al., 2020). In this way, a severe reduction of the microbial inhabitants may result in the decline of the soil's resistance to pollution (Pandey, 2018). The poisonous outcome of nano Fe can interrupt the cells' membranes by making the reactive oxygen compounds that are responsible for the death of the microbial cells (Wang et al., 2019). Nano Fe compounds can obstruct the assimilation of nutrients via the cell membranes in the microorganism, which delays their development and growth (Hong et al., 2021). Compounds of Nano Fe have not proven to have any outcome on the development and growth of colonies of fungi. Studies have measured how the poisonous outcome of NMs can be reduced by covering them with some organic polymers (Pandey, 2018). Studies have also proved that microbes produce specific polysaccharides and enzymes that defend the poisonous action of NMs (Torres et al., 2019). In addition to their positive outcome on the

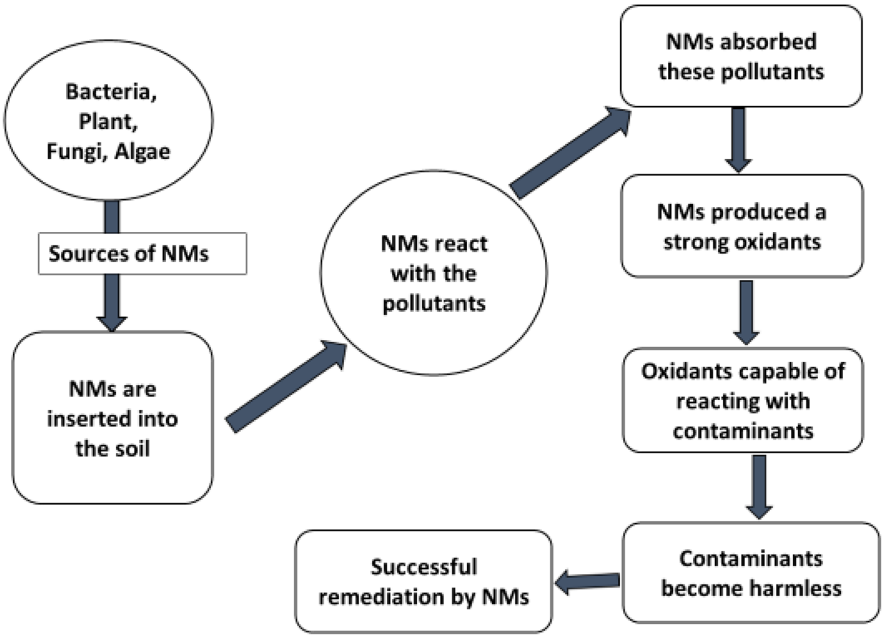


Fig. 1 Outline the mechanism of soil remediation by NMs

exclusion of the pollutants, NMs might act together with both biotic and abiotic substances in positive and negative pathways. There are some characteristics of microorganisms, such as a high growth rate, less expenditure demand, simple culture techniques, and fewer environmental exposures, which help produce the biosynthesis of NMs (Alghuthaymi et al., 2015). Additionally, the utilization of NMs in an environment that has soils interacting with various organisms and NMs can influence the NBR of the polluted soils (Gomes et al., 2021). Some of the NMs utilized in this area contain carbon-related and metal-related NMs (Zhai et al., 2015; White et al., 2009).

BR and its significant role

BR is an advanced technique that proposes an environmentally amicable and economically viable substitute to eliminate pollutants from the environment (Rahman et al., 2022; Chauhan et al., 2020). The three major processes of BR are the utilization of plants, microbes, and enzymes (Rahman et al., 2022; Ojuederie & Babalola, 2017). The organic compounds are degraded from a contaminated environment by microbes such as bacteria, fungi, and yeast (Vieyra et al., 2015). Bacteria and fungi are utilized in the areas of breaking down different contaminants as shown in Table 3. The method of BR is significant in conserving and maintaining contaminated environments such as agricultural soil. Environmental biotechnology involves the application of genetic engineering to determine the competence and value of the utilization of microorganisms for reducing the environmental burden of toxic substances (Enamala et al., 2019). There are several microorganisms in an environment cultivating at different growth rates, and their plentiful diversity of functions has been observed (Stewart, 2012).

Bacteria Bacteria are utilized in different applications in the environment through a variety of techniques. Among them, the BR technique is being used for a variety of purposes (Kadiyala et al., 2018). It was reported that the bacteria are used in breaking down the heavy metals and other pollutants via the route of BR (Khan et al., 2021). For example, bacteria identified as *Deinococcusradioduranscan* remedy heavy metals found in agricultural soil and is a non-pathogenic solvent bacterium (Appukuttan et al., 2006). Some of the genes recognized in *Deinococcus radiodurans* for breaking down metals, such as the *merA* reductase gene that encodes for the mercuric ion reductase, are extremely poisonous to humans (De et al., 2014). Some of the bacteria (such as *Bacillus algicola, Sphingobium* sp., *Rhodococcus* sp., *Bosea* sp., *Phenylobacterium* sp., *Candida viswanathii, Bacillus subtilis,* etc.) are used to degrade various pollutants (aromatic hydrocarbons, polynuclear aromatic hydrocarbons) in agricultural soils as shown in Table 3.

Fungi Fungi also play a vital role in the areas of nanotechnology because their main task is the removal of poisonous pollutants (Huang et al., 2018). Some fungi produce extracellular synthesis (metabolites or enzymes) during their growth and development as a result of the BR. It was demonstrated that the catalytic outcomes of the enzymes being released by fungi, such as *Fusarium oxysporum, Trichoderma viride, Aspergillus niger, Coriolus Versicolor, Candida glabrata, Aspergillus oryzae, and Fusarium semitectum,* are applied to remove the exclusion contaminants and poisonous effluents nearby in the environment (Vázquez-Núñez et al., 2020) as shown in Table 3. Not only bacteria and fungi but also some species of algae (*Chlorella* sp.) and yeast (*Lipomyceskononenkoae*) may play an important role in breaking down pollutants.

Combined application of NMs and NBR in agricultural soil

The practice of combining NMs and NBR technology can remove pollutants from the environment as shown in Table 4. Different types of NMs have been used for the remediation of pollutants, for example, bimetallic nanoparticles (BNPs), enzymes, titanium dioxide (TiO2), nZVI, nanoscale zeolites, carbon nanotubes, and three metal oxides(nZVI, TiO2, and CNTs), which are applied in agricultural soil remediation (Table 4).

Vázquez-Núñez et al. (2020) reported that responses of living organisms depend on the environmental conditions, types of pollutants, and NMs utilizations. Different types of NMs are being utilized to increase the microbial degradation of contaminants. Kim et al.

Table 3 List of bacteria and fungi used in BR techniques

Name of the bacteria	Compounds degraded	Sources	References
Deinococcusr adiodurans,	Degradation of radioactive pollutants; metal remediation; bioprecipitation of uranium	Polluted soils; mixed waste environments; dilute nuclear waste	Appukuttan et al. (2006), Brim et al. (2000)
Sphingobium sp., *Rhodococcus sp. Bosea* sp., *and Phenylobacterium* sp.	Degradation petroleum hydrocarbons	Saline soils	Rodríguez-Uribe et al. (2021)
Bacillus algicola	Degradation of hydrocarbons	Polluted soils	Lee et al. (2018), Gutierrez et al. (2014)
Rhodococcussoli; Rhodococcus sp.	Degradation of hydrocarbons	Contaminated soil	Jayasena and Perera (2021), Li et al. (2013)
Isoptericolachiayiensis	Degradation of hydrocarbons	Contaminated soils	Jayasena and Perera (2021), Lee et al. (2018)
Pseudoalteromonasagarivorans;	Degradation of hydrocarbons	Polluted soils	Jayasena and Perera (2021), Lee et al. (2018)
Micro bacterium sp.	Aromatic hydrocarbons	Polluted soils	Qin et al. (2017), Sheng et al. (2009)
Pseudomonas sp.	Aromatic hydrocarbons; Petroleum hydrocarbons; Crude oil, pristine and dioxin compounds; Naphthalene	Polluted soils; Saline soils	Hentati et al. (2021), Mahjoubi et al. (2021), Rodríguez-Uribe et al. (2021), Obayori et al. (2009)
Pseudomonas aeruginosa	Aliphatic hydrocarbons	Contaminated seawater	Hentati et al. (2021)
Candida viswanathii	Phenanthrene; Coupling azo dye; Benzopyrene	Polluted soils	Ali et al. (2021a, b), Enamala et al. (2019)
Bacillus subtilis	Phenols; Aromatic hydrocarbons	Contaminated soils	Kotoky and Pandey (2021), Enamala et al. (2019)
Fungi			
Agaricus bisporus	Polycyclic aromatic hydrocarbons (PAHs) of penanthrene and pyrene; Heavy metal	Polluted soils	Saravanan et al. (2021)
Coprinellus radians	Polynuclear aromatic hydrocarbons (PAHs); Diverse xenobiotics like dyes, hydrocarbons, and phenolic compounds	Contaminated soils	Ghosh and Mukherji (2021)
Gloeophyllum striatum	Chlorinated organic pollutant	Polluted soils	Jambon et al. (2019)
Rhizophagus intraradices	Total petroleum hydrocarbons (TPH)	Agricultural soils	Zuzolo et al. (2021)
Pleurotus pulmonarius	Polychlorinated biphenyl	Contaminated soil	Sebastian et al. (2021)
Phanerochaete chrysosporium	Polycyclic hydrocarbons	Soils	Imam et al. (2022)
Pleurotus ostreatus	Hydrocarbon's degradation	Contaminated soils	Mayans et al. (2021)
Acaulospora colombiana, Claroideoglomus etunicatum, Rhizophagusintraradices, Rhizophagusclarus, Rhizophagus irregularis	Hydrocarbons' degradation; Total petroleum hydrocarbons (TPH)	Agricultural soils	Zuzolo et al. (2021)
Arbuscular mycorrhizal fungi (AMF)	Total hydrocarbons; Petroleum hydrocarbon	Soil	Martínez-Hernández et al. (2021), Solís-Ramos et al. (2021)
Calendula officinalis	Cadmium	Soil	Enamala et al. (2019)
Aspergillus sydowii	Polyaromatic hydrocarbon	Hypersaline conditions	Peidro-Guzmán et al. (2021)
Aspergillus sp., *Trichoderma* sp.	Lead, iron, cadmium, chromium, zinc, nickel, mercury, and arsenic,	Marine environment, wastewater, and on land	Enamala et al. (2019)

Table 4 Combined practice of NMs and NBR technology used in agricultural soil remediation

NMs	Organisms or biological systems used	Contaminant degraded	Short explanation of the success	Removal efficiency	References
nZVI	*Sphingomonas* sp. PH-07	Polybrominated diphenyl ethers (PBDEs)	Effective for the breakdown of PBDEs via reductive debromination monitored by biological oxidation. This process can clue to a remediation tactic for extremely halogenated environmental contaminants	High	Kim et al. (2012)
nZVI	Any second metal or microorganism	Polychlorinated biphenyls (PCBs)	There is high remediation of PCB with a fast reaction time	(78–99%)	Jing et al. (2018)
CNT	Arthrobacter sp.	Polychlorinated biphenyls (PCBs)	Utilizing carbon nanotubes (CNT) and Arthrobacter sp. to break down PCBs, it was proved that the batch container with CNT had the maximum breakdown percentage	High	Pereira et al. (2014)
Magnetic nanoparticles	*Rhodococcusrhodochrous*	d-2-chloropheno, 4-chlorophenol, 2, 3-dichlorophenol	Cells were immobilized by using k-carrageenan and Fe3O4 NPS and it was demonstrated that they were capable of breaking down pollutants	30%	Hou et al. (2016)
Bimetallic iron-based nanoparticles	Tobacco plants	Hexabromocyclododecane (HBCD)	The entire hexabromocyclododecane (HBCD) was eliminated from contaminated soil	27%	Le et al. (2019)
Polyvinylpyrrolidone (PVP)-coated iron oxide nanoparticles	*Halomonas* sp.	Pb, Cd	The combined approach improved metal removal and shortened metal remediation times	Approximately 100%	Cao et al. (2020)

Table 4 (continued)

NMs	Organisms or biological systems used	Contaminant degraded	Short explanation of the success	Removal efficiency	References
Unzipped carbon tube (CNT)	Enzyme organophosphate hydrolase–MWNT paper	Organophosphates and heavy metals	The combination of CNT with the enzyme organophosphate hydrolase remediates Organophosphates and heavy metals from contaminated soil	22%	Fosso-Kankeu et al. (2014), Mechrez et al. (2014)
Nano sponge (Cyclodextrin-based, highly cross-linked polymers)	Two organo-clays (Dellite 67G and Dellite 43 B)	Triclopyr (3,5,6-Trichloro-2-pyridinyloxyacetic acid)	The combination of Nano sponge with two organo-clays remediates triclopyr	92%	Baglieri et al. (2013)

(2012) observed that nano-bio treatment utilizing nZVI and diphenyl ether in a mixture using bacteria *Sphingomonas* sp. can remove polybrominated diphenyl ethers (PBDEs). *Sphingomonas* sp. PH-07 could produce in nZVI concentrations up to a high concentration of 5 gl^{-1} and contribute to the bio-deprivation of PBDEs (Kim et al., 2012). Similarly, Jing et al. (2018) found that the mixture of nZVI NM with any second metal or microorganism is used for the remediation of deeply contaminated places. The mixture also eliminates polychlorinated biphenyls (PCBs) from soil polluted by modifier oil. It was proved that nZVI significantly improved the soil washing efficacy by decreasing the interfacial tension between the oil and soil stages and removed 90% of PCBs (Bhattacharya et al., 2016). The mixture nZVI is utilized as pretreatment in the bioremediation of nitrate anions, PCBs, pesticides, heavy metals, radionuclides, and chlorinated volatile organic compounds (cVOCs) (Bhattacharya et al., 2016; de Lima et al., 2012). Pereira et al. (2014) reported that a combination utilizing carbon nanotubes (CNT) and *Arthrobacter* sp. break down PCBs. They also found that the batch container with CNT was the highest breakdown percentage compared to other carbon NMS.

Hou et al. (2016) demonstrated the biodegradation of chlorophenol immobilized in magnetic NPS in a 100-mL batch container through *Rhodococcus rhodochrous*. The cells were immobilized by using k-carrageenan and Fe_3O_4 NPS and were capable of breaking down d-2-chlorophenol, 4-chlorophenol, 2, 3-dichlorophenol (Hou et al., 2016). Le et al. (2019) found that the combination of bimetallic iron dependent on NMs with tobacco plants is utilized to remove hexabromocyclododecane (HBCD). The unzipped carbon tube (CNT) combined with the enzyme organophosphate hydrolase removed the organophosphates and heavy metals from contaminated soil (Mechrez et al., 2014). Several previous studies have been attempted to increase the synergistic outcome of NM and BR practices and to elaborate on their biological and chemical interaction either in water or soil (Vázquez-Núñez et al., 2020).

Conclusions and prospects

The outcomes of nanoparticles on microorganisms in adjustable soil situations are critical to the remediation methods for the enhancement of the breakdown of soil pollutants. Nano bioremediation (NBR) relies primarily on the utilization of nanomaterials (NMs) to decrease the pollutants to equal levels that are favorable to biodegradation and then stimulate the biodegradation of the pollutants to spread the risk-based levels. The NMs are being used in various applications of NMs in building solids and in medicating several environmental contaminants. Consequently, the remediation of pollutants by the usage of current technology was not found to be efficient and effective in cleaning up the environment. It is helpful to develop the contaminant elimination competence and the combination of bioremediation (BR) technologies with NMs to eliminate contaminates. The NMs were applied to increase the exclusion of pollutants and narrate their interaction with abiotic and biotic elements during the remediation. So, NMs can be utilized for BR, which not only has a less toxic consequence on microorganisms but will also develop the microbial activity of the different pollutants in the agricultural soils, which offers an excellent opportunity for upcoming researchers.

Acknowledgements The authors wish to thank Dr. Patti Fisher, Professional editor employed by Editor World LLC for checking the English languages and grammatical errors. The authors would like to thank the UGC under Islamic University, Bangladesh (Ref. No. 141/Edu/IU-2019/331) for partial funding.

Author contribution Md. Rasel Rana, Jannatul Ferdous, and Md. Mizanur Rahman comprehended and planned the study, carried out the analysis, wrote the manuscript; and prepared the graphs and illustrations; Muntaha Binte Mukhles, Nazmul Huda, Fahida Rahman, Md. Amdadul Huq, Md. Yousof Ali, and Meherab Hossain Rafi contributed to the critical revision of the manuscript and wrote the manuscript; Md. Mizanur Rahman supervised the whole work, and all authors approved the final manuscript.

Funding This study was funded by the UGC under Islamic University, Bangladesh (Ref. No. 141/Edu/IU-2019/331) for partial funding.

Data availability The corresponding author M. Mizanur Rahman is responsible for all data and materials.

Declarations

Ethics approval This article does not include any studies by any of the authors that used human or animal participants. All authors are conscious and accept responsibility for the manuscript.

Consent for publication No part of the manuscript content has been published or accepted for publication elsewhere.

Competing interests The authors declare no competing interests.

References

Abboud, Y., Saffaj, T., Chagraoui, A., El Bouari, A., Brouzi, K., Tanane, O., & Ihssane, B. (2014). Biosynthesis, characterization and antimicrobial activity of copper oxide nanoparticles (CONPs) produced using brown alga extract (*Bifurcariabifurcata*). *Applied Nanoscience, 4*(5), 571–576. https://doi.org/10.1007/s13204-013-0233-x

Alazaiza, M. Y., Albahnasawi, A., Ali, G. A., Bashir, M. J., Copty, N. K., Amr, S. S. A., & Al Maskari, T. (2021). Recent advances of nanoremediation technologies for soil and groundwater remediation: A review. *Water*, *13*(16), 2186. https://doi.org/10.3390/w13162186

Alghuthaymi, M. A., Almoammar, H., Rai, M., Said-Galiev, E., & Abd-Elsalam, K. A. (2015). Myconanoparticles: Synthesis and their role in phytopathogens management. *Biotechnology & Biotechnological Equipment, 29*(2), 221–236. https://doi.org/10.1080/13102818.2015.1008194

Ali, S. S., Al-Tohamy, R., Koutra, E., Kornaros, M., Khalil, M., Elsamahy, T., & Sun, J. (2021a). Coupling azo dye degradation and biodiesel production by manganese-dependent peroxidase producing oleaginous yeasts isolated from wood-feeding termite gut symbionts. *Biotechnology for Biofuels, 14*(1), 1–25. https://doi.org/10.1186/s13068-021-01906-0

Ali, S., Mehmood, A., & Khan, N. (2021b). Uptake, translocation, and consequences of nanomaterials on plant growth and stress adaptation. *Journal of Nanomaterials*. https://doi.org/10.1155/2021/6677616

Ambashta, R. D., & Sillanpää, M. (2010). Water purification using magnetic assistance: A review. *Journal of Hazardous Materials, 180*(1–3), 38–49. https://doi.org/10.1016/j.jhazmat.2010.04.105

Appukuttan, D., Rao, A. S., & Apte, S. K. (2006). Engineering of Deinococcus radiodurans R1 for bioprecipitation of uranium from dilute nuclear waste. *Applied and Environmental Microbiology*, *72*(12), 7873–7878. https://doi.org/10.1128/AEM.01362-06

Arčon, I., Piccolo, O., Paganelli, S., & Baldi, F. (2012). XAS analysis of a nanostructured iron polysaccharide produced anaerobically by a strain of *Klebsiella oxytoca*. *Biometals, 25*(5), 875–881. https://doi.org/10.1007/s10534-012-9554-6

Arunachalam, R., Dhanasingh, S., Kalimuthu, B., Uthirappan, M., Rose, C., & Mandal, A. B. (2012). Photosynthesis of silver nanoparticles using *Coccinia grandis* leaf extract and its application in the photocatalytic degradation. *Colloids and Surfaces B: Biointerfaces, 94*, 226–230. https://doi.org/10.1016/j.colsurfb.2012.01.040

Baglieri, A., Nègre, M., Trotta, F., Bracco, P., & Gennari, M. (2013). Organo-clays and nanosponges for acquifer bioremediation: Adsorption and degradation of triclopyr. *Journal of Environmental Science and Health - Part B Pesticides, Food Contaminants, and Agricultural Wastes, 48*(9), 784–792. https://doi.org/10.1080/03601234.2013.780943

Balciunas, E. M., Martinez, F. A. C., Todorov, S. D., de Melo Franco, B. D. G., Converti, A., & de Souza Oliveira, R. P. (2013). Novel biotechnological applications of bacteriocins: A review. *Food Control, 32*(1), 134–142. https://doi.org/10.1016/j.foodcont.2012.11.025

Banerjee, A., Choudhury, M., Chakravorty, A., Raghavan, V., Biswas, B., Sana, S. S., Rayan, R. A., Abhishek, N., Lala N. L., & Ramakrishna, S. (2021). Microbiological degradation of organic pollutants from industrial wastewater.In *Nanobiotechnology for Green Environment* (pp. 83–114). CRC Press. https://doi.org/10.1201/9780367461362

Bhattacharya, K., Mukherjee, S. P., Gallud, A., Burkert S. C., Bistarelli, S., Bellucci, S., Bottini, M., Star, A., & Fadeel, B. (2016). Biological interactions of carbon-based nanomaterials: From coronation to degradation. *Nanomedicine: Nanotechnology, Biology, and Medicine, 12*(2), 333–351. https://doi.org/10.1016/j.nano.2015.11.011

Bezbaruah, A. N., Thompson, J. M., & Chisholm, B. J. (2009). Remediation of alachlor and Atrazine contaminated water with zero-valent iron nanoparticles. Journal of Environmental Science and science Health, Part B 44(6), 518-524. https://doi.org/10.1080/03601230902997501

Binupriya, A. R., Sathishkumar, M., Vijayaraghavan, K., & Yun, S. I. (2010). Bioreduction of trivalent aurum to nano-crystalline gold particles by active and inactive cells and cell-free extract of *Aspergillus oryzae* var. viridis. *Journal of Hazardous Materials, 177*(1–3), 539–545. https://doi.org/10.1016/j.jhazmat.2009.12.066

Boparai, H. K., Joseph, M., & O'Carroll, D. M. (2013). Cadmium (Cd2+) removal by nano zerovalent iron: Surface analysis, effects of solution chemistry and surface complexation modeling. *Environmental Science and Pollution Research, 20*(9), 6210–6221. https://doi.org/10.1007/s11356-013-1651-8

Brim, H., Mc Farlan, S.C., Fredrickson, J. K, Minton, K. W., Zhai, M., Wackett, L. P, & Daly, M. J. (2000). Engineering Deinococcus radiodurans for metal remediation in radioactive mixed waste environments. *Natural Biotechnology*. https://doi.org/10.1038/71986

Cao, X., Alabresm, A., Chen, Y. P., Decho, A. W., & Lead, J. (2020). Improved metal remediation using a combined bacterial and nanoscience approach. *Science of the Total Environment, 704*, 135378. https://doi.org/10.1016/j.scitotenv.2019.135378

Chang, M. C., & Kang, H. Y. (2009.) Remediation of pyrene-contaminated soil by synthesized nanoscale zero-valent iron particles. Journal of Environmental Science and science Health, Part A 44(6), 576-582.https://doi.org/10.1080/10934520902784609

Chauhan, R., Yadav, H. O., & Sehrawat, N. (2020). Nanobioremediation: A new and a versatile tool for sustainable environmental cleanup-Overview. *Journal of Materials and Environmental Science, 11*(4), 564–573.

Chaung, S. H., Wu, P. F., Kao, Y. L., Yan, W., & Lien, H. L. (2014). Nanoscale zero-valent iron for sulfide removal from digested piggery wastewater. *Journal of Nanomaterials, 2014*(518242). https://doi.org/10.1155/2014/518242

China, C. R., Maguta, M. M., Nyandoro, S. S., Hilonga, A., Kanth, S. V., & Njau, K. N. (2020). Alternative tanning technologies and their suitability in curbing environmental pollution from the leather industry: A comprehensive review. *Chemosphere*, *254*, 126804. https://doi.org/10.1016/j.chemosphere.2020.126804

Choi, H., Al-Abed, S.R., Agarwal, S., & Dionysiou, D.D. (2008). Synthesis of reactive nano-Fe/Pd bimetallic system-impregnated activated carbon for the simultaneous adsorption and dechlorination of PCBs. *Journal of materials chemistry*, *20*(11), 3649–3655. https://doi.org/10.1021/cm8003613

Corso, C. R., & De Almeida, A. C. M. (2009). Bioremediation of dyes in textile effluents by Aspergillus oryzae. *Microbial ecology*, *57*(2), 384. https://doi.org/10.1007/s00248-008-9459-7

Cutting, R. S., Coker, V. S., Telling, N. D., Kimber, R. L., Pearce, C. I., Ellis, B. L., & Lloyd, J. R. (2010). Optimizing Cr (VI) and Tc (VII) remediation through nanoscale biomineral engineering. *Environmental Science & Technology, 44*(7), 2577–2584. https://doi.org/10.1021/es902119u

Das, S., Chakraborty, J., Chatterjee, S., & Kumar, H. (2018). Prospects of biosynthesized nanomaterials for the remediation of organic and inorganic environmental contaminants. *Environmental Science: Nano, 5*(12), 2784–2808. https://doi.org/10.1039/C8EN00799C

Das, S., Sen, B., & Debnath, N. (2015). Recent trends in nanomaterials applications in environmental monitoring and remediation. *Environmental Science and Pollution Research, 22*(23), 18333–18344. https://doi.org/10.1007/s11356-015-5491-6

De, J., Dash, H. R., & Das, S. (2014). Mercury pollution and bioremediation—a case study on biosorption by a mercury-resistant marine bacterium. *In Microbial biodegradation and bioremediation Elsevier science*, 137–166. https://doi.org/10.1016/B978-0-12-800021-2.00006-6

de Lima, R., Seabra, A. B., & Durán, N. (2012). Silver nanoparticles: A brief review of cytotoxicity and genotoxicity of chemically and biogenically synthesized nanoparticles. *Journal of Applied Toxicology, 32*(11), 867–879. https://doi.org/10.1002/jat.2780

Dhillon, G. S., Kaur, S., Verma, M., & Brar, S. K. (2012). Biopolymer-based nanomaterials: potential applications in bioremediation of contaminated wastewaters and soils. In Comprehensive Analytical Chemistry Vol. 59, 91-129 Elsevier. https://doi.org/10.1016/B978-0-444-56328-6.00003-7

Dobrucka, R., & Długaszewska, J. (2016). Biosynthesis and antibacterial activity of ZnO nanoparticles using Trifolium pratense flower extract. *Saudi Journal of Biological Sciences, 23*(4), 517–523. https://doi.org/10.1016/j.sjbs.2015.05.016

Enamala, M. K., Sruthi, P. D., Sarkar, S., Chavali, M., Vasavi, I., & Kuppam, C. (2019). Nanobioremediation: A novel and sustainable biological advancement for ecological cleanup. In *Nanotechnology in Biology and Medicine* (pp. 245–257). CRC Press. https://doi.org/10.1201/9780429259333

Fan, F. L., Qin, Z., Bai, J., Rong, W. D., Fan, F. Y., Tian, W., & Zhao, L. (2012). Rapid removal of uranium from aqueous solutions using magnetic Fe3O4@ SiO2 composite particles. *Journal of Environmental Radioactivity, 106*, 40–46. https://doi.org/10.1016/j.jenvrad.2011.11.003

Fosso-Kankeu, E., Mulaba-Bafubiandi, F., & Mishra, A.K. (2014). Prospects for immobilization of microbial sorbents on carbon nanotubes for biosorption: Bioremediation of heavy metalspolluted water. *Application of Nanotechnology in Water Research, 39*. https://doi.org/10.1002/9781118939314

Gangula, A., Podila, R., Karanam, L., Janardhana, C., & Rao, A. M. (2011). Catalytic reduction of 4-nitrophenol using biogenic gold and silver nanoparticles derived from Breyniarhamnoides. *Langmuir, 27*(24), 15268–15274. https://doi.org/10.1021/la2034559

Ganguly, P., Breen, A., & Pillai, S. C. (2018). Toxicity of nanomaterials: Exposure, pathways, assessment, and recent advances. *ACS Biomaterials Science & Engineering, 4*(7), 2237–2275. https://doi.org/10.1021/acsbiomaterials.8b00068

Ghosh, P., & Mukherji, S. (2021). Environmental contamination by heterocyclic polynuclear aromatic hydrocarbons and their microbial degradation. *Bioresource Technology*, *341*, 125860. https://doi.org/10.1016/j.biortech.2021.125860

Gomes, S. I., Scott-Fordsmand, J. J., & Amorim, M. J. (2021). Alternative test methods for (nano) materials hazards assessment: Challenges and recommendations for regulatory preparedness. *Nano Today*, *40*, 101242. https://doi.org/10.1016/j.nantod.2021.101242

Guo, M., Weng, X., Wang, T., & Chen, Z. (2017). Biosynthesized iron-based nanoparticles used as a heterogeneous catalyst for the removal of 2, 4-dichlorophenol. *Separation and Purification Technology, 175*, 222–228. https://doi.org/10.1016/j.seppur.2016.11.042

Gupta, N., Singh, H. P., & Sharma, R. K. (2010). Single-pot synthesis: Plant mediated gold nanoparticles catalyzed reduction of methylene blue in presence of stannous chloride. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 367*(1–3), 102–107. https://doi.org/10.1016/j.colsurfa.2010.06.022

Gupta, A., Tandon, M., & Kaur, A. (2020). Role of metallic nanoparticles in water remediation with special emphasis on sustainable synthesis: A review. *Nanotechnology for Environmental Engineering, 5*(3), 1–13. https://doi.org/10.1007/s41204-020-00092-y

Gutierrez, T., Rhodes, G., Mishamandani, S., Berry, D., Whitman, W. B., Nichols, P. D., & Aitken, M. D. (2014). Polycyclic aromatic hydrocarbon degradation of phytoplankton-associated Arenibacter spp. and description of Arenibacteralgicola sp. nov., an aromatic hydrocarbon-degrading bacterium. *Applied and Environmental Microbiology, 80*(2), 618–628. https://doi.org/10.1128/AEM.03104-13

Hasanin, M., Elahnasawy, M. A., & Shehabeldine, A.M. (2021). Ecofriendly preparation of silver nanoparticles-based nanocomposite stabilized by polysaccharides with antibacterial, antifungal and antiviral activities. Biometals 34, 1313–1328. https://doi.org/10.1007/s10534-021-00344-7

Hentati, D., Chebbi, A., Mahmoudi, A., Hadrich, F., Cheffi, M., Frikha, I., &Chamkha, M. (2021). Biodegradation of hydrocarbons and biosurfactants production by a newly halotolerant Pseudomonas sp. strain isolated from contaminated seawater. *Biochemical Engineering Journal*, *166*, 107861. https://doi.org/10.1016/j.bej.2020.107861

Hong, J., Wang, C., Wagner, D. C., Gardea-Torresdey, J. L., He, F., & Rico, C. M. (2021). Foliar application of nanoparticles: Mechanisms of absorption, transfer, and multiple impacts. *Environmental Science: Nano, 8*(5), 1196–1210. https://doi.org/10.1039/D0EN01129K

Hooshyar, Z., RezanejadeBardajee, G., & Ghayeb, Y. (2013). Sonication enhanced removal of nickel and cobalt ions from polluted water using an iron based sorbent. *Journal of Chemistry*. https://doi.org/10.1155/2013/786954

Hou, J., Liu, F., Wu, N., Ju, J., & Yu, B. (2016). Efficient biodegradation of chlorophenols in aqueous phase by magnetically immobilized aniline-degrading Rhodococcusrhodochrous strain. *Journal of Nanobiotechnology, 14*(1), 1–8. https://doi.org/10.1186/s12951-016-0158-0

Huang, D., Guo, X., Peng, Z., Zeng, G., Xu, P., Gong, X., & Liu, C. (2018). White rot fungi and advanced combined biotechnology with nanomaterials: Promising tools for endocrine-disrupting compounds biotransformation. *Critical Reviews in Biotechnology, 38*(5), 671–689. https://doi.org/10.1080/07388551.2017.1386613

Huang, C. C., Lo, S. L., & Lien, H. L. (2012). Zero-valent copper nanoparticles for effective dechlorination of dichloromethane using sodium borohydride as a reductant. *Chemical Engineering Journal*, *203*, 95–100. https://doi.org/10.1016/j.cej.2012.07.002

Huang, J., Wang, W., Lin, L., Li, Q., Lin, W., Li, M., & Mann, S. (2009). A general strategy for the biosynthesis of gold nanoparticles by traditional Chinese medicines and their potential application as catalysts. Chemistry–An Asian Journal, 4(7), 1050-1054. https://doi.org/10.1002/asia.200900064

Huda, N., Khanom, A., Mizanur Rahman, M., Huq, A., Rahman, M., & Banu, N. A. (2021). Biochemical process and functional genes of arsenic accumulation in bioremediation: Agricultural soil. *International Journal of Environmental Science and Technology*, 1–20. https://doi.org/10.1007/s13762-021-03655-x

Huq, M. A., Ashrafudoulla, M., Rahman, M. M., Balusamy, S. R., & Akter, S. (2022). Green synthesis and potential antibacterial applications of bioactive silver nanoparticles: A review. *Polymers, 14*(4), 742. https://doi.org/10.3390/polym14040742

Imam, A., Suman, S. K., Kanaujia, P. K., & Ray, A. (2022). Biological machinery for polycyclic aromatic hydrocarbons degradation: A review. *Bioresource Technology, 343*, 126121. https://doi.org/10.1016/j.biortech.2021.126121

Jambon, I., Thijs, S., Torres-Farradá, G., Rineau, F., Weyens, N., Carleer, R., & Vangronsveld, J. (2019). Fenton-mediated biodegradation of Chlorendic acid–a highly chlorinated organic pollutant–by fungi isolated from a polluted site. *Frontiers in microbiology*, 1892. https://doi.org/10.3389/fmicb.2019.01892

Javaid, M. A., Zia, K. M., Iqbal, A., Ahmad, S., Akram, N., Liu, X., & Awais, M. (2020). Utilization of waxy corn starch as an efficient chain extender for the preparation of polyurethane elastomers. *International Journal of Biological Macromolecules, 148*, 415–423. https://doi.org/10.1016/j.ijbiomac.2020.01.011

Jayasena, S., & Perera, M. (2021). Microbial bioremediation of petroleum hydrocarbons. In *Microbial Rejuvenation of Polluted Environment* (pp. 263–291). Springer, Singapore. https://doi.org/10.1007/978-981-15-7447-4_11

Jing, R., Fusi, S., & Kjellerup, B. V. (2018). Remediation of polychlorinated biphenyls (PCBs) in contaminated soils and sediment: State of knowledge and perspectives. *Frontiers in Environmental Science, 6*, 79. https://doi.org/10.3389/fenvs.2018.00079

Johari, W. L. W., Diamessis, P. J., & Lion, L. W. (2010). Mass transfer model of nanoparticle-facilitated contaminant transport in saturated porous media. *Water Research, 44*(4), 1028–1037. https://doi.org/10.1016/j.watres.2009.03.033

Kadiyala, U., Kotov, N. A., & VanEpps, J. S. (2018). Antibacterial metal oxide nanoparticles: Challenges in interpreting the literature. *Current Pharmaceutical Design, 24*(8), 896–903. https://doi.org/10.2174/1381612824666180219130659

Kanchi, S., Kumar, G., Lo, A. Y., Tseng, C. M., Chen, S. K., Lin, C. Y., & Chin, T. S. (2018). Exploitation of de-oiled jatropha waste for gold nanoparticles synthesis: A green approach. *Arabian Journal of Chemistry, 11*(2), 247–255.255. https://doi.org/10.1016/j.arabjc.2014.08.006

Karimi, E., & Mohseni Fard, E. (2017). Nanomaterial effects on soil microorganisms. In *Nanoscience and plant–soil systems* (pp. 137–200). Springer, Cham. https://doi.org/10.1007/978-3-319-46835-8_5

Karlapudi, A. P., Venkateswarulu, T. C., Tammineedi, J., Kanumuri, L., Ravuru, B. K., ramu Dirisala, V., & Kodali, V. P. (2018). Role of biosurfactants in bioremediation of oil pollution-a review. *Petroleum, 4*(3), 241–249. https://doi.org/10.1016/j.petlm.2018.03.007

Khan, F. S. A., Mubarak, N. M., Tan, Y. H., Khalid, M., Karri, R. R., Walvekar, R., & Mazari, S. A. (2021). A comprehensive review on magnetic carbon nanotubes and carbon nanotube-based buckypaper for removal of heavy metals and dyes. *Journal of Hazardous Materials, 413*, 125375. https://doi.org/10.1016/j.jhazmat.2021.125375

Khezami, L., Taha, K. K., Ghiloufi, I., & El Mir, L. (2016). Adsorption and photocatalytic degradation of malachite green by vanadium doped zinc oxide nanoparticles. *Water Science and Technology, 73*(4), 881–889. https://doi.org/10.2166/wst.2015.555

Kim, Y. M., Murugesan, K., Chang Y. Y., Kim, E. J., & Chang, Y. S. (2012). Degradation of polybrominated diphenyl ethers by a sequential treatment with nanoscale zero valent iron and aerobic biodegradation. *Journal of Chemical Technology and Biotechnology*, *87*,(2), 216–224. https://doi.org/10.1002/jctb.2699

Kim, Y. M., Murugesan, K., Chang, Y. Y., Kim, E. J., & Chang, Y. S. (2012). Degradation of polybrominated diphenyl ethers by a sequential treatment with nanoscale zero valent iron and aerobic biodegradation. *Journal of Chemical Technology & Biotechnology, 87*(2), 216–224. https://doi.org/10.1002/jctb.2699

Kim, A., Muthuchamy, N., Yoon, C., Joo, S. H., & Park, K. H. (2018). MOF-derived Cu@ Cu2O nanocatalyst for oxygen reduction reaction and cycloaddition reaction. *Nanomaterials, 8*(3), 138. https://doi.org/10.3390/nano8030138

Kim, J. H., Tratnyek, P. G., & Chang, Y. S. (2008). Rapid dechlorination of polychlorinated dibenzo-p-dioxins by bimetallic and nanosized zerovalent iron. *Environmental Science Technology*, *42*(11), 4106–4112. https://doi.org/10.1021/es702560k

Kotoky, R., & Pandey, P. (2021). The genomic attributes of Cd-resistant, hydrocarbonoclastic Bacillus subtilis SR1 for rhizodegradation of benzo (a) pyrene under co-contaminated conditions. *Genomics, 113*(1), 613–623. https://doi.org/10.1016/j.ygeno.2020.09.057

Kos, L., Michalska, K. and Perkowski, J., 2014. Decomposition of non-ionic surfactant Tergitol TMN-10 by the Fenton process in the presence of iron oxide nanoparticles. *Environmental Science and Pollution Research, 21*(21), 12223–12232.

Kruefu, V., Ninsonti, H., Wetchakun, N., Inceesungvorn, B., Pookmanee, P., & Phanichphant, S. (2012). Photocatalytic degradation of phenol using Nb-loaded ZnO nanoparticles. *Engineering Journal, 16*(3), 91–100. https://doi.org/10.4186/ej.2012.16.3.91

Kumar, G., Kumar, R., Hwang, S. W., & Umar, A. (2014). Photocatalytic degradation of direct red-23 dye with ZnO nanoparticles. *Journal of Nanoscience and Nanotechnology, 14*(9), 7161–7166. https://doi.org/10.1166/jnn.2014.9229

Kumar, K. M., Mandal, B. K., Kumar, K. S., Reddy, P. S., & Sridhar, B. (2013). Biobased green method to synthesise palladium and iron nanoparticles using Terminalia chebula aqueous extract. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 102*, 128–133. https://doi.org/10.1016/j.saa.2012.10.015

Kumar, K. P., Paul, W., & Sharma, C. P. (2011). Green synthesis of gold nanoparticles with Zingiber officinale extract: Characterization and blood compatibility. *Process Biochemistry, 46*(10), 2007–2013. https://doi.org/10.1016/j.procbio.2011.07.011

Kumar, R. R., & Priyadharsani, K. P, Thamaraiselvi, K. (2012). Mycogenic synthesis of silver nanoparticles by the Japanese environmental isolate Aspergillus tamarii. Journal of Nanoparticle Research. https://doi.org/10.1007/s11051-012-0860-2

Kungwani, N., Shukla, S. K., Rao, T. S., & Das, S. (2022). Biofilm-mediated bioremediation of polycyclic aromatic hydrocarbons: current status and future perspectives. In *Microbial Biodegradation and Bioremediation* (pp. 547–570). Elsevier. https://doi.org/10.1016/B978-0-323-85455-9.00021-7

Le, T. T., Yoon, H., Son, M. H., Kang, Y. G., & Chang, Y. S. (2019). Treatability of hexabromocyclododecane using Pd/Fe nanoparticles in the soil-plant system: Effects of humic acids. *Science of the Total Environment, 689*, 444–450. https://doi.org/10.1016/j.scitotenv.2019.06.290

Lee, C., Kim, J. Y., Lee, W. I., Nelson, K. L., Yoon, J., & Sedlak, D. L. (2008). Bactericidal effect of zero-valent iron nanoparticles on Escherichia coli. *Environment Science Technology*, *42*(13), 4927–4933. https://doi.org/10.1021/es800408u

Lee, C. L., Lee, H. Y., Tseng, K. H., Andy Hong, P. K., & Jou, C. J. G. (2011). Enhanced dechlorination of chlorobenzene by microwave-induced zero-valent iron: Particle effects and activation energy. *Environmental Chemistry Letters, 9*(3), 355–359. https://doi.org/10.1007/s10311-010-0286-y

Lee, D. W., Lee, H., Kwon, B. O., Khim, J. S., Yim, U. H., Kim, B. S., & Kim, J. J. (2018). Biosurfactant-assisted bioremediation of crude oil by indigenous bacteria isolated from Taean beach sediment. *Environmental*

Pollution, 241, 254–264. https://doi.org/10.1016/j.envpol.2018.05.070

Li, C., Zhou, Z. X., Jia, X. Q., Chen, Y., Liu, J., & Wen, J. P. (2013). Biodegradation of crude oil by a newly isolated strain Rhodococcus sp. JZX-01. *Applied Biochemistry and Biotechnology, 171*(7), 1715–1725. https://doi.org/10.1007/s12010-013-0451-4

Lim, T. T., Feng, J., & Zhu B. W. (2007). Kinetic and mechanistic examinations of reductive transformation pathways of brominated methanes with nano-scale Fe and Ni/Fe particles. Water research 41(4), 875-883. https://doi.org/10.1016/j.watres.2006.11.019

Loick, N., Hobbs, P. J., Hale, M. D., & Jones, D. L. (2009). Bioremediation of poly-aromatic hydrocarbon (PAH)-contaminated soil by composting. Critical Review of Environmental Science and Technology 39(4), 271-332. https://doi.org/10.1080/10643380701413682

Lu, F., & Astruc, D. (2020). Nanocatalysts and other nanomaterials for water remediation from organic pollutants. *Coordination Chemistry Reviews, 408*, 213180. https://doi.org/10.1016/j.ccr.2020.213180

Liu, J., Morales-Narváez, E., Vicent, T., Merkoçi, A., & Zhong, G. H. (2018). Microorganism-decorated nanocellulose for efficient diuron removal. Chemical Engineering Journal, 354, 1083–1091. https://doi.org/10.1016/j.cej.2018.08.035

Mahdavi, M., Namvar, F., Ahmad, M. B., & Mohamad, R. (2013). Green biosynthesis and characterization of magnetic iron oxide (Fe3O4) nanoparticles using seaweed (Sargassum muticum) aqueous extract. *Molecules, 18*(5), 5954–5964. https://doi.org/10.3390/molecules18055954

Mahdavian, A. R., & Mirrahimi, M. A. S. (2010). Efficient separation of heavy metal cations by anchoring polyacrylic acid on superparamagnetic magnetite nanoparticles through surface modification. *Chemical Engineering Journal, 159*(1–3), 264–271. https://doi.org/10.1016/j.cej.2010.02.041

Mahjoubi, M., Aliyu, H., Neifar, M., Cappello, S., Chouchane, H., Souissi, Y., & Cherif, A. (2021). Genomic characterization of a polyvalent hydrocarbonoclastic bacterium Pseudomonas sp. strain BUN14. *Scientific Reports, 11*(1), 1–13. https://doi.org/10.1038/s41598-021-87487-2

Mallikarjunaiah, S., Pattabhiramaiah, M., & Metikurki, B. (2020). Application of nanotechnology in the bioremediation of heavy metals and wastewater management. In *Nanotechnology for food, agriculture, and environment* (pp. 297–321). Springer, Cham. https://doi.org/10.1007/978-3-030-31938-0_13

Mandal, A., Dutta, A., Das, R., & Mukherjee, J. (2021). Role of intertidal microbial communities in carbon dioxide sequestration and pollutant removal: A review. *Marine Pollution Bulletin, 170*, 112626. https://doi.org/10.1016/j.marpolbul.2021.112626

Martínez-Hernández, I. A., Rivera-Cruz, M. D. C., Carballar-Hernández, S., Trujillo-Narcía, A., Ortíz-García, C. F., Hernández-Galvez, G., & Alarcón, A. (2021). Arbuscular mycorrhizal colonization in a mangrove forest exposed to weathering oil for half a century. *Water, Air, & Soil Pollution, 232*(1), 1–18. https://doi.org/10.1007/s11270-021-04986-8

Mayans, B., Camacho-Arévalo, R., García-Delgado, C., Antón-Herrero, R., Escolástico, C., Segura, M. L., & Eymar, E. (2021). An assessment of Pleurotusostreatus to remove sulfonamides, and its role as a biofilter based on its own spent mushroom substrate. *Environmental Science and Pollution Research, 28*(6), 7032–7042. https://doi.org/10.1007/s11356-020-11078-3

Mazarji, M., Minkina, T., Sushkova, S., Mandzhieva, S., Bidhendi, G. N., Barakhov, A., & Bhatnagar, A. (2021). Effect of nanomaterials on remediation of polycyclic aromatic hydrocarbons-contaminated soils: A review. *Journal of Environmental Management*, *284*, 112023. https://doi.org/10.1016/j.jenvman.2021.112023

Mechrez, G., Krepker, M. A., Harel, Y., Lellouche, J. P., & Segal, E. (2014). Biocatalytic carbon nanotube paper: A 'one-pot' route for fabrication of enzyme-immobilized membranes for organophosphate bioremediation. *Journal of Materials Chemistry B, 2*(7), 915–922. https://doi.org/10.1039/C4TB90005G

Mishra, A., Tripathy, S. K., Wahab, R., Jeong, S. H., Hwang, I., Yang, Y. B., ... & Yun, S. I. (2011). Microbial synthesis of gold nanoparticles using the fungus Penicillium brevicompactum and their cytotoxic effects against mouse mayo blast cancer C2C12 cells. *Applied Microbiology and Biotechnology, 92*(3), 617–630.https://doi.org/10.1007/s00253-011-3556-0

Moholkar, D. N., Havaldar, D. V., Potadar, R. S., & Pawar, K. D. (2020). Optimization of biogenic synthesis of colloidal metal nanoparticles. In *Colloids-Types, Preparation and Applications*. IntechOpen. https://doi.org/10.5772/intechopen.94853

Morones, J. R, Elechiguerra, J. L, Camacho, A., Holt, K., Kouri, J. B., Ramírez, J. T., & Yacaman, M. J. (2005) .The bactericidal effect of silver nanoparticles. Nanotechnology 16(10), 2346. https://doi.org/10.1088/0957-4484/16/10/059

Murgueitio, E., Cumbal, L., Abril, M., Izquierdo, A., Debut, A., & Tinoco, O. (2018). Green synthesis of iron nanoparticles: Application on the removal of petroleum oil from contaminated water and soils. *Journal of Nanotechnology*, 2018. https://doi.org/10.1155/2018/4184769

Murínová, S., & Dercová, K. (2014). Response mechanisms of bacterial degraders to environmental contaminants on the level of cell walls and cytoplasmic membrane. *International Journal of Microbiology*, 2014. https://doi.org/10.1155/2014/873081

Murthy, H. A., Abebe, B., Prakash, C. H., & Shantaveerayya, K. (2018). A review on green synthesis of Cu and CuO nanomaterials for multifunctional applications. *Material Science Research India, 15*(3), 279–295. https://doi.org/10.13005/msri/150311

Nanda, A., & Saravanan, M. (2009). Biosynthesis of silver nanoparticles from Staphylococcus aureus and its antimicrobial activity against MRSA and MRSE. *Nanomedicine: Nanotechnology, Biology, and Medicine*, *5*(4), 452–456. https://doi.org/10.1016/j.nano.2009.01.012

Narayanan, K. B., & Sakthivel, N. (2011). Synthesis and characterization of nano-gold composite using Cylindrocladiumfloridanum and its heterogeneous catalysis in the degradation of 4-nitrophenol. *Journal of Hazardous*

Materials, 189(1–2), 519–525. https://doi.org/10.1016/j.jhazmat.2011.02.069

Nematollahzadeh, A., Seraj, S., & Mirzayi, B. (2015). Catecholamine coated maghemite nanoparticles for the environmental remediation: Hexavalent chromium ions removal. *Chemical Engineering Journal, 277*, 21–29. https://doi.org/10.1016/j.cej.2015.04.135

Obayori, O. S., Ilori, M. O, Adebusoye, S. A., Oyetibo, G. O, Omotayo, A. E, & Amund, O.O. (2009) .Degradation of hydrocarbons and biosurfactant production by Pseudomonas sp. strain LP1. *World Journal of Microbiology and Biotechnology*, *25*(9), 1615–1623. https://doi.org/10.1007/s11274-009-0053-z

O'Carroll, D., Sleep, B., Krol, M., Boparai, H., & Kocur, C. (2013). Nanoscale zero valent iron and bimetallic particles for contaminated site remediation. *Advances in Water Resources, 51*, 104–122. https://doi.org/10.1016/j.advwatres.2012.02.005

Ojuederie, O. B., & Babalola, O. O. (2017). Microbial and plant-assisted bioremediation of heavy metal polluted environments: A review. *International Journal of Environmental Research and Public Health, 14*(12), 1504. https://doi.org/10.3390/ijerph14121504

Pandey, G. (2018). Prospects of nanobioremediation in environmental cleanup. *Oriental Journal of Chemistry*, *34*(6), 2838. https://doi.org/10.13005/ojc/340622

Pardeshi, S. K., & Patil, A. B (2009.) Solar photocatalytic degradation of resorcinol a model endocrine disrupter in water using zinc oxide. *Journal of Hazard Materials*, *163*(1), 403–409.https://doi.org/10.1016/j.jhazmat.2008.06.111

Patel, A. B., Shaikh, S., Jain, K. R., Desai, C., & Madamwar, D. (2020). Polycyclic aromatic hydrocarbons: Sources, toxicity, and remediation approaches. *Frontiers in Microbiology*, 2675. https://doi.org/10.3389/fmicb.2020.562813

Peidro-Guzmán, H., Pérez-Llano, Y., González-Abradelo, D., Fernández-López, M. G., Dávila-Ramos, S., Aranda, E., & Batista-García, R. A. (2021). Transcriptomic analysis of polyaromatic hydrocarbon degradation by the halophilic fungus Aspergillus sydowii at hypersaline conditions. *Environmental Microbiology, 23*(7), 3435–3459. https://doi.org/10.1111/1462-2920.15166

Pereira, R. A., Pereira, M. F. R., Alves, M. M., & Pereira, L. (2014). Carbon based materials as novel redox mediators for dye wastewater biodegradation. *Applied Catalysis B: Environmental, 144*, 713–720. https://doi.org/10.1016/j.apcatb.2013.07.009

Phumying, S., Labuayai, S., Swatsitang, E., Amornkitbamrung, V., & Maensiri, S. (2013). Nanocrystalline spinel ferrite (MFe2O4, M= Ni Co, Mn, Mg, Zn) powders prepared by a simple aloe vera plant-extracted solution hydrothermal route. *Materials Research Bulletin, 48*(6), 2060–2065. https://doi.org/10.1016/j.materresbull.2013.02.042

Phumying, S., Labuayai, S., Thomas, C., Amornkitbamrung, V., Swatsitang, E., & Maensiri, S. (2013b). Aloe vera plant-extracted solution hydrothermal synthesis and magnetic properties of magnetite (Fe3O4) nanoparticles. *Applied Physics A, 111*(4), 1187–1193. https://doi.org/10.1007/s00339-012-7340-5

Pradeep, T. (2009). Noble metal nanoparticles for water purification: a critical review. Thin solidfilms 517(24), 6441-6478. https://doi.org/10.1016/j.tsf.2009.03.195

Qin, W., Zhu, Y., Fan, F., Wang, Y., Liu, X., Ding, A., & Dou, J. (2017). Biodegradation of benzo (a) pyrene by Microbacterium sp. strain under denitrification: Degradation pathway and effects of limiting electron acceptors or carbon source. *Biochemical Engineering Journal, 121*, 131–138. https://doi.org/10.1016/j.bej.2017.02.001

Rahman, M. M., Haque, Z., Huda, N., Huq, M., Rauf, M., Fahim, M., & Arif, M. (2022). Microplastics and synthetic polymers in agricultural soils: biodegradation, analytical methods and their impact on environment. In *Advances in Bioremediation and Phytoremediation for Sustainable Soil Management* (pp. 261–281). Springer, Cham. https://doi.org/10.1007/978-3-030-89984-4_17

Raliya, R., & Tarafdar, J. C. (2014). Biosynthesis and characterization of zinc, magnesium and titanium nanoparticles: An eco-friendly approach. *International Nano Letters, 4*(1), 1–10. https://doi.org/10.1007/s40089-014-0093-8

Ramezani, M., Rad, F. A., Ghahari, S., Ghahari, S., & Ramezani, M. (2021). Nano-bioremediation application for environment contamination by microorganism. In *Microbial Rejuvenation of Polluted Environment* (pp. 349–378). Springer, Singapore. https://doi.org/10.1007/978-981-15-7455-9_14

Rasheed, T., Bilal, M., Iqbal, H. M., & Li, C. (2017). Green biosynthesis of silver nanoparticles using leaves extract of Artemisia vulgaris and their potential biomedical applications. *Colloids and Surfaces B: Biointerfaces, 158*, 408–415. https://doi.org/10.1016/j.colsurfb.2017.07.020

Reddy, A. V. B., Yusop, Z., Jaafar, J., Reddy, Y. V. M., Aris, A. B., Majid, Z. A., & Madhavi, G. (2016). Recent progress on Fe-based nanoparticles: Synthesis, properties, characterization, and environmental applications. *Journal of environmental chemical engineering, 4*(3), 3537–3553. https://doi.org/10.1016/j.jece.2016.07.035

Rizwan, M., Singh, M., Mitra, C. K., & Morve, R. K. (2014). Ecofriendly application of nanomaterials: Nanobioremediation. *Journal of Nanoparticles*, *2014*. https://doi.org/10.1155/2014/431787

Rodríguez-Uribe, M. L., Peña-Cabriales, J. J., del Carmen Rivera-Cruz, M., & Délano-Frier, J. P. (2021). Native bacteria isolated from weathered petroleum oil-contaminated soils in Tabasco, Mexico, accelerate the degradation of petroleum hydrocarbons in saline soil microcosms. *Environmental Technology & Innovation, 23*, 101781. https://doi.org/10.1016/j.eti.2021.101781

Sankar, R., Maheswari, R., Karthik, S., Shivashangari, K. S., & Ravikumar, V. (2014). Anticancer activity of Ficus religiosa engineered copper oxide nanoparticles. *Materials Science and Engineering: C, 44*, 234–239. https://doi.org/10.1016/j.msec.2014.08.030

Sanna, V., Pala, N., Alzari, V., Nuvoli, D., & Carcelli, M. (2016). ZnO nanoparticles with high degradation efficiency of organic dyes under sunlight irradiation. *Materials Letters, 162*, 257–260. https://doi.org/10.1016/j.matlet.2015.10.031

Saravanan, A., Kumar, P. S., Vo, D. V. N., Jeevanantham, S., Karishma, S., & Yaashikaa, P. R. (2021). A review on catalytic-enzyme degradation of toxic environmental pollutants: Microbial enzymes. *Journal of Hazardous Materials, 419*, 126451. https://doi.org/10.1016/j.jhazmat.2021.126451

Saravanan, M., & Nanda, A. (2010). Extracellular synthesis of silver bionanoparticles from Aspergillus clavatus and its antimicrobial activity against MRSA and MRSE. *Colloids and Surfaces B: Biointerfaces, 77*(2), 214–218. https://doi.org/10.1016/j.colsurfb.2010.01.026

Sathishkumar, P., Mangalaraja, R. V., Anandan, S., & Ashokkumar, M. (2013). Photocatalytic degradation of ternary dye mixture in aqueous environment using gold nanoparticles loaded amino and mercapto functionalized TiMCM-41 nanocatalysts in the presence of visible light. *Separation and Purification Technology, 102*, 67–74. https://doi.org/10.1016/j.seppur.2012.09.030

Sebastian, C.A., Alvarenga, A. E., Lopez, C. A. M., Zapata, P. D., & Fonseca, M. I. (2021). Proteomic insight on the polychlorinated biphenyl degrading mechanism of Pleurotuspulmonarius LBM 105. *Chemosphere*, *265*, 129093. https://doi.org/10.1016/j.chemosphere.2020.129093

Sebastian, V., Arruebo, M., & Santamaria, J. (2014). Reaction engineering strategies for the production of inorganic nanomaterials. *Small (weinheim an Der Bergstrasse, Germany), 10*(5), 835–853. https://doi.org/10.1002/smll.201301641

Shahwan, T., Sirriah, S. A., Nairat, M., Boyacı, E., Eroğlu, A. E., Scott, T. B., & Hallam, K. R. (2011). Green synthesis of iron nanoparticles and their application as a Fenton-like catalyst for the degradation of aqueous cationic and anionic dyes. *Chemical Engineering Journal, 172*(1), 258–266. https://doi.org/10.1016/j.cej.2011.05.103

Sharma, J. K., Akhtar, M. S., Ameen, S., Srivastava, P., & Singh, G. (2015). Green synthesis of CuO nanoparticles with leaf extract of Calotropis gigantea and its dye-sensitized solar cells applications. *Journal of Alloys and Compounds, 632*, 321–325. https://doi.org/10.1016/j.jallcom.2015.01.172

Shende, S., Ingle, A. P., Gade, A., & Rai, M. (2015). Green synthesis of copper nanoparticles by Citrus medica Linn. (Idilimbu) juice and its antimicrobial activity. *World Journal of Microbiology and Biotechnology, 31*(6), 865–873. https://doi.org/10.1007/s11274-015-1840-3

Sheng, X. F., He, L. Y., Zhou, L., & Shen, Y. Y. (2009). Characterization of Microbacterium sp. F10a and its role in polycyclic aromatic hydrocarbon removal in low-temperature soil. *Canadian Journal of Microbiology*, *55*(5), 529–535. https://doi.org/10.1139/W09-005

Singh, R., Behera, M., & Kumar, S. (2020). Nano-bioremediation: An innovative remediation technology for treatment and management of contaminated sites. In *Bioremediation of industrial waste for environmental safety* (pp. 165–182). Springer, Singapore. https://doi.org/10.1007/978-981-13-3426-9_7

Sinha, T., & Ahmaruzzaman, M. (2015). Green synthesis of copper nanoparticles for the efficient removal (degradation) of dye from aqueous phase. *Environmental Science and Pollution Research, 22*(24), 20092–20100. https://doi.org/10.1007/s11356-015-5223-y

Smuleac, V., Varma, R., Sikdar, S., & Bhattacharyya, D. (2011). Green synthesis of Fe and Fe/Pd bimetallic nanoparticles in membranes for reductive degradation of chlorinated organics. *Journal of Membrane Science, 379*(1–2), 131–137. https://doi.org/10.1016/j.memsci.2011.05.054

Solís-Ramos, L. Y., Coto-López, C., & Andrade-Torres, A. (2021). Role of arbuscular mycorrhizal symbiosis in remediation of anthropogenic soil pollution. *Symbiosis, 84*(3), 321–336. https://doi.org/10.1007/s13199-021-00774-4

Song, H., & Carraway, E. R. (2005). Reduction of chlorinated ethanes by nanosized zero-valent iron: kinetics, pathways, and effects of reaction conditions. *Environmental Science & Technology, 39*(16), 6237–6245. https://doi.org/10.1021/es048262e

Srivastava, V., Gusain, D., & Sharma, Y. C. (2013). Synthesis, characterization, and application of zinc oxide nanoparticles (n-ZnO). *Ceramics International, 39*(8), 9803–9808. https://doi.org/10.1016/j.ceramint.2013.04.110

Stewart, E. J. (2012). Growing unculturable bacteria. *Journal of Bacteriology, 194*(16), 4151–4160. https://doi.org/10.1128/JB.00345-12

Teng, Y., Wang, X., Li, L., Li, Z., & Luo, Y. (2015). Rhizobia and their bio-partners as novel drivers for functional remediation in contaminated soils. *Frontiers in Plant Science, 6*, 32. https://doi.org/10.3389/fpls.2015.00032

Thakur, S., Sharma, S., Thakur, S., & Rai, R. (2018). Green synthesis of copper nano-particles using Asparagus adscendensroxb. Root and leaf extract and their antimicrobial activities. *International Journal of Current Microbiology and Applied Sciences, 7*(4), 683–694. https://doi.org/10.20546/ijcmas.2018.704.077

Torres, F. G., Troncoso, O. P., Pisani, A., Gatto, F., & Bardi, G. (2019). Natural polysaccharide nanomaterials: An overview of their immunological properties. *International Journal of Molecular Sciences, 20*(20), 5092. https://doi.org/10.3390/ijms20205092

Torres-Martínez, C.L., Kho, R., Mian, O.I. and Mehra, R.K. (2001). Efficient photocatalytic degradation of environmental pollutants with mass-produced ZnS nanocrystals. *Journal of colloid and interface science*, *240*(2), 525–532.

Vardhan, K. H., Kumar, P. S., & Panda, R. C. (2019). A review on heavy metal pollution, toxicity and remedial measures: Current trends and future perspectives. *Journal of Molecular Liquids, 290*, 111197. https://doi.org/10.1016/j.molliq.2019.11119

Vázquez-Núñez, E., Molina-Guerrero, C. E., Peña-Castro, J. M., Fernández-Luqueño, F., & de la Rosa-Álvarez, M. (2020). Use of nanotechnology for the bioremediation of contaminants: A review. *Processes, 8*(7), 826. https://doi.org/10.3390/pr8070826

Vieyra, H., San Martín‐Martínez, E., Juárez, E., Figueroa‐López, U., & Aguilar‐Méndez, M. A. (2015). Biodegradation process of a blend of thermoplastic unripe banana flour—polyethylene under composting: Identification of the biodegrading agent. *Journal of Applied Polymer Science, 132*(29). https://doi.org/10.1002/app.42258

Visentin, C., da Silva Trentin, A. W., Braun, A. B., & Thomé, A. (2021). Nano scale zero valent iron production methods applied to contaminated sites remediation: An overview of production and environmental aspects. *Journal of Hazardous Materials, 410*, 124614. https://doi.org/10.1016/j.jhazmat.2020.124614

Wang, D., Saleh, N. B., Sun, W., Park, C. M., Shen, C., Aich, N., & Su, C. (2019). Next-generation multifunctional carbon–metal nanohybrids for energy and environmental applications. *Environmental Science & Technology, 53*(13), 7265–7287. https://doi.org/10.1021/acs.est.9b01453

Wang, T., Lin, J., Chen, Z., Megharaj, M., & Naidu, R. (2014). Green synthesized iron nanoparticles by green tea and eucalyptus leaves extracts used for removal of nitrate in aqueous solution. *Journal of Cleaner Production, 83*, 413–419. https://doi.org/10.1016/j.jclepro.2014.07.006

Wei, Y., Ke, L., Kong, J., Liu, H., Jiao, Z., Lu, X., & Sun, X. W. (2012). Enhanced photo electrochemical water-splitting effect with a bent ZnO nanorod photoanode decorated with Ag nanoparticles. Nanotechnology, 23(23), 235401. https://doi.org/10.1088/0957-4484/23/23/235401

White, R. J., Luque, R., Budarin, V. L., Clark, J. H. & Macquarrie, D. J. (2009). Supported metal nanoparticles on porous materials. Methods and applications. *Chemical Society Reviews*, *38*(2), 481–494.

Yaqoob, A. A., Parveen, T., Umar, K., & Mohamad Ibrahim, M. N. (2020). Role of nanomaterials in the treatment of wastewater: A review. *Water, 12*(2), 495. https://doi.org/10.3390/w12020495

Yaqub, A., Malkani, N., Shabbir, A., Ditta, S. A., Tanvir, F., Ali, S., & Ullah, R. (2020). Novel biosynthesis of copper nanoparticles using Zingiber and Allium sp. with synergic effect of doxycycline for anticancer and bactericidal activity. *Current Microbiology, 77*(9), 2287–2299. https://doi.org/10.1007/s00284-020-02058-4

Thomassin-Lacroix, E., Eriksson, M., Reimer, K., & Mohn, W. (2002). Biostimulation and bioaugmentation for on-site treatment of weathered diesel fuel in Arctic soil. *Applied Microbiology and Biotechnology,* 59(4), 551–556. https://doi.org/10.1007/s00253-002-1038-0

Yuvak kumar, R., Suresh, J., Saravanakumar, B., Nathanael, A. J., Hong, S. I., & Rajendran, V. (2015). Rambutan peels promoted biomimetic synthesis of bioinspired zinc oxide nanochains for biomedical applications. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 137*, 250–258. https://doi.org/10.1016/j.saa.2014.08.022

Zamborini, F. P., Bao, L., & Dasari, R. (2012). Nanoparticles in measurement science. *Analytical Chemistry, 84*(2), 541–576. https://doi.org/10.1021/ac203233q

Zhai, H., Liang, Z., Chen, Z., Wang, H., Liu, Z., Su, Z. & Zhou, Q. (2015). Simultaneous detection of metronidazole and chloramphenicol by differential pulse stripping voltammetry using a silver nanoparticles/sulfonate functionalized graphene modified glassy carbon electrode. Electrochimica Acta, 171, pp.105-113.

Zhou, H., Fan, T., Han, T., Li, X., Ding, J., Zhang, D., Guo, Q., & Ogawa, H. (2009). Bacteria-based controlled assembly of metal chalcogenide hollow nanostructures with enhanced light-harvesting and photocatalytic properties. *Nanotechnology*, *20*(8), 085603. https://doi.org/10.1088/0957-4484/20/8/085603

Zuzolo, D., Guarino, C., Tartaglia, M., & Sciarrillo, R. (2021). Plant-soil-microbiota combination for the removal of total petroleum hydrocarbons (TPH): An in-field experiment. *Frontiers in Microbiology*, 3611. https://doi.org/10.3389/fmicb.2020.621581