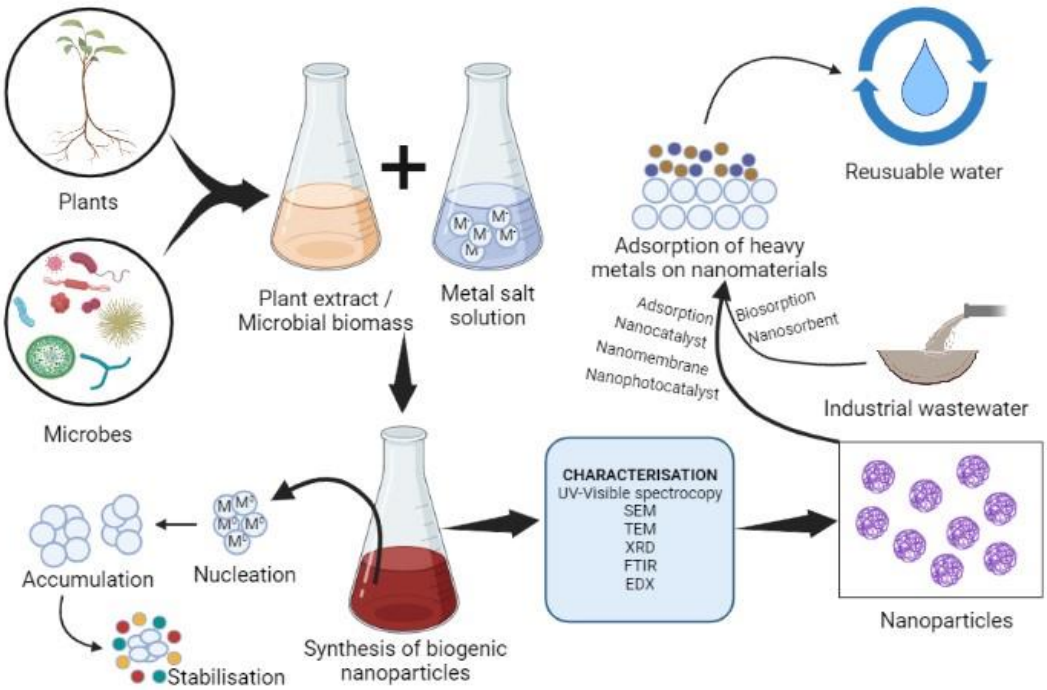
Research Article

Journal of Environmental Nanotechnology

Effective Bio-mediated Nanoparticles for Bioremediation of Toxic Metal Ions from Wastewater – A Review

V. Yamini, V. Devi Rajeswari*
Department of Biomedical Sciences, School of Biosciences and Technology, VIT University, Vellore, TN, India
Received: 11.04.2023 Accepted: 17.04.2023 Published: 30-06-2023
*vdevirajeswari@vit.ac.in

GRAPHICAL ABSTRACT



ABSTRACT

Water tainted with colours, heavy metal ions and biological toxins, contributes to eutrophication, which in turn contributes to a variety of fatal diseases in humans and other animals, owing to the fact that water purification equipment and methods are not cheap. Due to this, there is a pressing need for economically viable wastewater treatment components. Eco-friendly nanomaterials, highly efficient and selective, renewable, earth-abundant and stable, have emerged as a major priority, overcoming a number of challenges and restrictions. Currently, the combination of nanomaterials and biomolecules from plants, including polyphenols, amines and other components, as well as intracellular and extracellular enzymes found in microbes, has become more significant in bioremediation. Biogenic nanoparticles are favoured because they are easy to expand for large-scale biosynthesis, maintain stability for an extended period, consume less time, are eco-friendly, and do not produce any detrimental by-products. The processes of nano-bioremediation and wastewater treatment are discussed in detail in this review. It primarily focuses on synthesizing, characterizing and applying bio-mediated nanoparticles, which actively remove heavy metal ions from wastewater, without adversely affecting individuals or other living things, especially in aquatic environments.

Keywords: Heavy metal ions; Biogenic nanoparticles; Nano-bioremediation; Wastewater treatment; Inorganic pollutants.

1. INTRODUCTION

Water contamination is a significant environmental concern, and population growth and rising economic demands contribute to water scarcity. Rainwater harvesting, underground water storage, water conservation measures, desalination, recycling, and reusing wastewater are among the methods utilized to address the lack of fresh water (Raouf *et al*. 2019). Water pollution negatively impacts the aquatic ecosystem and it is responsible for serious illnesses in humans and animals (Inyinbor *et al*. 2018). Fever, vomiting, diarrhea, nausea, weight loss and abdominal pain are some initial symptoms and indicators. However, when the condition progresses, it can lead to severe illnesses like cancer, kidney failure, renal failure and cardiovascular damage. Cholera, a water-borne bacterial infection that killed millions of people worldwide in 1817, is only one example of the pandemic diseases that water pollution may make this globe more susceptible to.

Different types of contaminants present in the wastewater include biological or chemical, 80 – 90 % of the sludge accumulation, and the discharge of sewage sludge leads to a decrease in the nutrient enrichments and dissolved oxygen level (DO) in waterbodies. Chemical pollutants include hydrocarbons, nitrogenous compounds, phosphorus, pesticides, pharmaceutical residues, heavy metal cations, and detergents. Microbiological contamination includes animal and human faecal materials, which contains abundant microorganisms like bacteria, virus, fungi and protozoans, which causes severe medical complications in humans and other living beings. Currently, the usage percentage of biological methods in wastewater treatment is increased and is more significant among people (Akpor, 2011; Ohoro *et al.* 2019).

Biological treatment consists of microorganisms found naturally; it can convert the dissolved oxygen into huge biomass, and the sedimentation process removes the completely fine particles from the wastewater. The biological method is preferable to the chemical method because microorganisms utilize organic matter as the major source for their growth; even the amount of sludge produced during the process is also low compared to the chemical process and the wastewater treatment mechanism is illustrated in Fig. 1. Other techniques include aeration and anaerobic lagoons, filters like biological and percolating/trickling filters, activated sludge, aerobic bioreactors and oxidation ponds.

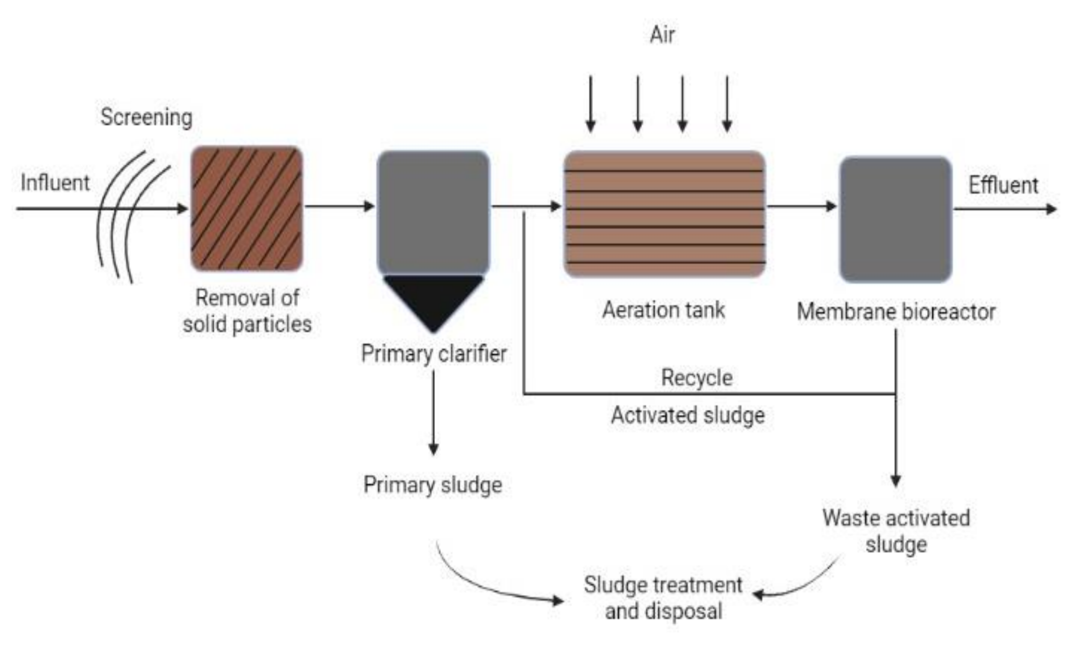


Fig. 1: Illustration of wastewater treatment

Wastewater consists of degradable and non-degradable solid wastes and contains other compounds like Polypropylene Co-polymers (PPCPs), Volatile Organic Compounds (VOCs), Endocrine Disrupting Chemicals (EDCs), toxins, heavy metals such as Nickel (Ni), Mercury (Hg), Lead (Pb), Chromium (Cr), Cadmium (Cd), Zinc (Zn), Arsenic (As), organic and inorganic pollutants. Industrial growth and human activities are the foremost things to meliorate the concentration of heavy metal ions contaminants in wastewater. The presence of heavy metals causes severe diseases, including human carcinogens and central nervous system damage (Qasem *et al.* 2021). Almost many heavy metals may exhibit toxicity even in lower concentrations (Simeonov *et al.* 2010). Lead, mercury, nickel, arsenic, zinc, cadmium, iron, silver, manganese, boron, calcium, thallium, cobalt, copper and chromium are the most common inorganic pollutants which are found in wastewater. These metal ions are released by dye, fertilizers, bleaching agents, pesticides, mordants, fixing agents and pigment industries (Rao *et al.* 2010). The clearance of heavy metal ions should be achieved by adsorption techniques (natural and synthetic adsorbent), electrocoagulation, magnetic field, membranes, advanced oxidation process and photocatalytic methods. Depending upon the factors like the efficiency of removal, initial concentration of pH, the volume of the substance and other precise conditions, a suitable technique was performed to eliminate the metal ions from wastewater (Qasem *et al.* 2021). Heavy metal ions possess greater density than water. Ni, Pb and Cr concentrations are higher when compared with Hg, Tl and Cd in wastewater (Kinuthia *et al.* 2020).

This review mainly explains the importance of wastewater treatment methods and the nano-bioremediation process. Nano-bioremediation has a high advancement rate to eliminate the contaminants present in wastewater through synthesizing bio-mediated nanoparticles such as plants and microbes like bacteria, fungi, yeast, and algae, which is cheaper, environmentally safe, and needs less period consumption to achieve when compared with traditional wastewater treatment methods. At the same time, it possesses a high-efficiency rate for removing toxic metal pollutants and has no harmful side effects. Though the toxic metal ions are extracted using advanced techniques, the chemicals used for treatment and the presence of trace elements of ions after treatment may cause side effects to humans and disrupt the aquatic environment. Bio-mediated nanoparticles actively eliminate heavy metals without causing any impact on living beings and the environment.

2. BIOREMEDIATION

Bioremediation is an approach used to eliminate and turn contaminants from heavily toxic to less toxic substances by biological agents. The pollutants include metalloids, heavy metals, oils, hydrocarbons, pesticides and dyes. Biomass is used to mineralize and degrade organic compounds converted into water, carbon dioxide and nitrogen (Kapahi and Sachdeva, 2019). Four diverse methodologies were used to carry out the degradation of the toxic heavy metal remediation process. They are *in-situ* treatment, *ex-situ* treatment, *in-situ* containment and *ex-situ* containment (Rahman and Singh, 2020).

2.1. Nanobiotechnology

Nanobiotechnology is a collaborative study of Nanotechnology, which consists of the design, development and application of nanomaterials and nanodevices, and Biotechnology includes different functions of the biological site like microorganisms (Jain, 2005). Nanoparticles have specific properties like their uniform shape and high surface area, which help to permeate the cell membranes easily and perform other biochemical activities (Singh *et al.* 2019). Nanostructure materials are more potent catalysts and oxidoreduction activity for wastewater treatment due to their small size and wide surface area. Nanomaterials actively exclude organic and inorganic solvents, toxic metal ions, biological toxins, and pathogenic microbes in wastewater (Kumar *et al.* 2014). Polymeric nanoparticles, metal nanoparticles, carbon-based nanomaterials, metal-oxide nanoparticles, biopolymers and zeolites are broadly used to treat wastewater (Baruah *et al.* 2019). Nanotechnology-based pathways treat wastewater such as biosorption, adsorption, photocatalysis, nanofiltration, sensing, disinfection and monitoring (Jain *et al.* 2021).

3. NANOBIOREMEDIATION

The convergence of nanotechnology and bioremediation plays a considerable role in deteriorating the contaminants present in the environment and enhancing the advancement rate (Pete *et al.* 2021). In other words, impurities such as toxic metal ions, metalloids, and biotic and abiotic pollutants are eliminated by using nano-sized particles synthesized from biological materials like bacteria, fungi, algae and plants. The important applications include using clean, green nanomaterials to eliminate contaminants from wastewater and as a sensor to monitor environmental defects (Tratnyek and Johnson, 2006). The primary intention of nanotechnology to be incorporated into bioremediation is owing to the fact that it exhibits particles with small size (<100 nm), large surface area and stable chemical properties (Tosco *et al.* 2014).

3.1. Properties of Nanoparticles

A nanoparticle's size ranges between 1 to 100 nm and can change its physio-chemical properties (Mughal *et al.* 2021). Nanoparticles are categorized into two: organic and inorganic. A single crystalline nanoparticle is known as a nanocrystal and is also found to be amorphous. Nanoparticles exhibit various structures like platelets, cubes, spheres and tetrads (Gautam *et al.* 2021). Due to its low cost, environmentally safe, toxicity and rapid synthesis, the biological method is preferred for the synthesis process. Biological systems can self-organize and synthesize molecules with physical properties like shape, size, solubility, structure and surface area (Koul and Taak, 2018); chemical properties like surface chemistry, chemical composition, zeta potential and photocatalytic property (Rao and Biswas, 2009). Bio-mediated nanoparticles exhibit high surface and catalytic activity (Riddin *et al.* 2010). A capping agent in the microbe will decrease the possibility of nanoparticle aggregation and maintain stability for a prolonged time (Sudhakar *et al.* 2020).

3.2. Route of Synthesis

Nanoparticles were effectively synthesized by using physical, chemical, and biological methods. In a physical process, the larger particles deteriorate into smaller particles without any control of atoms (Tripathi *et al.* 2022). In contrast, the smaller particles are assembled to form nanoparticles by chemical methods such as laser pyrolysis, plasma spraying and Sol-gel. In a biological process, the formation of nanoparticles and capping takes place due to the release of biomolecule proteins present in biogenic substances, which are accountable for reducing the metal ions (Ingale and Chaudhari, 2013).

The working principle of bio-mediated nanoparticle synthesis mainly includes bio-precipitation and bio-reduction processes carried out by peptides, polyphenols, amino acids and other bioactive compounds which are produced by living beings (Park *et al*. 2011). These compounds act as a capping and stabilizing agent and prevent from the agglomeration of synthesized nanoparticles (Moulton *et al.* 2010). Plant extract can reduce metallic salts and results in the formation of Zn (Nava *et al*. 2017), Ag (Kumar et al., 2014), Cu (Lee *et al.*, 2011), Fe (Balamurugan *et al*. 2014), Au (Babu *et al.* 2011), Mn (Wright *et al*. 2016) and Pb nanoparticles containing different sizes and shapes. Microorganisms like bacteria, yeast, fungi and actinomycetes release a potent chemical that can oxidize or reduce the metal ions and synthesize the nanoparticles (Zhang *et al.*, 2011); the mechanism is illustrated in Fig. 2. Some biochemical reactions like acidolysis, alkylation, redoxolysis and complexolysis formed nanoparticles (Sathiyanarayanan *et al.* 2017). The disadvantage of synthesizing microbe-mediated nanoparticles is that they need an optimum environment for microbial growth and high costs (Hulkoti and Taranath, 2014). Synthesis of nanoparticles intracellularly can be achieved by disrupting the microbial cell (Deplanche and Macaskie, 2008). Algae contain phytochemicals used to immobilize and stabilize the nanoparticles (Jena *et al.* 2013).

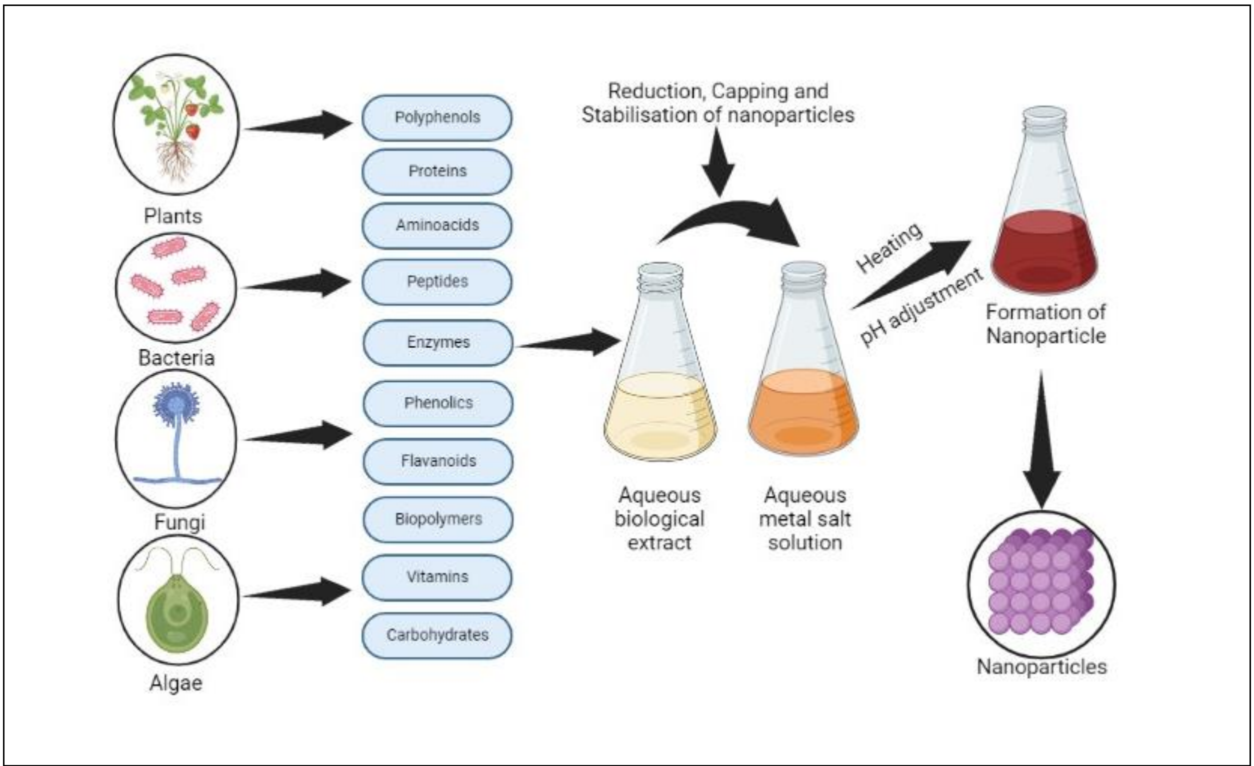


Fig. 2: Mechanism of bio-mediated nanoparticle synthesis

3.3 Characterization of Nanoparticles

Nanoparticles have distinctive qualities and characteristics that enable them valuable in a broad range of applications. It is essential to evaluate them through in-depth characterization for a range of applications to make sure they are appropriate for the purpose. This is accomplished by utilizing a variety of instruments and methods that can offer the necessary data. Dynamic light scattering (DLS), Fourier Transform Infrared (FT-IR), Energy-Dispersive X-ray Spectroscopy (EDS), Atomic Force Microscopy (AFM), Raman Spectroscopy (RS), and Scanning/Transmission Electron Microscopy (SEM/TEM) are among the most frequently utilized methods. The size, shape, structure, surface characteristics and interactions of nanoparticles with materials are studied using these methods (Hasan *et al.*, 2018).

3.3.1 Geometry

The distinctive qualities of nanoparticles that make them useful for specific applications are determined by their size and form. Modern tools with exceptional magnification and resolution are used to investigate the size and shape of nanoparticles at sizes smaller than 100 nm. High-Resolution Transmission Electron Microscopy (HRTEM) and Field-emission Scanning Electron Microscopy (FE-SEM), which can visualize and determine the atomic structure of nanoparticles, were among the best-known nanoscale imaging techniques. TEM may expose size, shape, agglomeration state and morphological complexity, by illuminating the nanoparticles with an electron beam.

3.3.2 Magnetic properties

The latest studies have seen a rise in interest in iron-based nanoparticles, necessitating research into their magnetic characteristics. Electron Paramagnetic Resonance (EPR), Superconducting Quantum Interference Devices (SQUID) and Vibrating-Sample Magnetometers (VSM) are a few of the methods to analyze the magnetic properties of the nanoparticles. EPR is used to find and locate paramagnetic centres and free radicals in chemical compounds. Interacting with the electrons in a material enables the evaluation of the physical characteristics of magnetic nanoparticles and the impact of the external magnetic field. VSM and SQUID are used for highly sensitive magnetic measurements, with sensitivities of 10^{-6} and 10^{-10} emu, correspondingly. Media like powders, nanoplatelets, and various solid and liquid samples are all characterized using SQUID.

3.3.3 Surface morphology

HRTEM and FE-SEM can visualize and determine the atomic structure of nanoparticles, which were among the best-known nanoscale imaging techniques. TEM may expose size, shape, agglomeration state and morphological complexity, by illuminating the nanoparticles with an electron beam. A further crucial method is Atomic Force Microscopy (AFM), which can function in air, liquid and vacuum and evaluate the topography, size and distribution of nanoparticles.

4. BIO-MEDIATED NANOPARTICLES

Water pollution is a major reason to cause severe human diseases because it contains many highly pathogenic microorganisms that are antibiotic-resistant and more difficult to remove from the wastewater. Bacteria can bind and concentrate the dissolved metal ions; it converts toxic into non-toxic metal ions (Tsekhmistrenko *et al.*, 2020). The algal cell wall encompasses abundant mucilaginous polysaccharides and carbonyl groups, which involve in metal uptake, and also it is rich in pigments like chlorophyll, antioxidants, minerals, phycobilins, proteins, and carbohydrates which help to reduce metal ions (Uzair *et al.*, 2020). Each microorganism and metal salt contains specific toxic metal degradation properties; some are listed in Table 1.

Table 1: Bioremediation of heavy metals by using bio-mediated nanoparticles

S. No.	Types of nanoparticles	Microorganisms	Metal degradation	Reference
1	Gold nanoparticles	*Gliomastix murorum, Cladosporium cladosporioides*	Copper ions	(Renu *et al*. 2017)
2	Laccase immobilized nanoparticles	*Pleurotus. ostreatus*	1: 9 of carbamazepine and bisphenol-A	(Ji *et al*. 2017)
3	Electro-spun cyclodextrin fibers	*Lysinibacillu* sp.	Ni(II) - 70%; Cr(VI) - 59%; Reactive black - 82%	(Oya *et al*. 2018)
4	Gold nanoparticles	*Rhizopus arrhizus, Penicillium spinulosum, Penicillium chrysogenum*	Zn - 60%	(Patil and Chandrasekaran, 2020)
5	Titanium nanoparticles	*Bacillus licheniforms*	Cu- 45%	(Agarwal and Singh, 2017)
6	Iron nanoparticles	*Pseudomonas aeruginosa, Bacillus subtilis*	Cr - 60%	(Benazir *et al*. 2010)
7	MgO nanoparticles	*Bacillus subtilis, P. licheniformis*	Ni - 70%	(Srivastava and Constanti, 2012)
8	Gold nanoparticles	*Penicillium chrysogenum*	Hg - 45%	(Park *et al*. 2011)
9	Iron nanoparticles	*Escherichia* sp., SINT7	Phosphate, Chloride ions	(Noman et al. 2020)

10	Zinc nanoparticles	*Alcaligenes sp., Moraxella sp.,*	Cd - 75%	(Patil and Chandrasekaran, 2020)
11	Gold nanoparticles	*Penicillium chrysogenum*	Pb - 60%	(Sharma and Sharma, 2022)
12	Zirconia-based nanoparticles	*Pseudomonas* sp.	Adsorption of tetracycline - 526.32 mg/g	(Debnath *et al*. 2020)
13	Electro-spun nano-fibers	*Pseudomonas* sp.	Methylene blue dye - 55 - 70%	(Sarioglu *et al*. 2017)
14	Silica nanoparticles	Actinomycetes	80% decolorization	(Mohanraj *et al*. 2022)

Plants and microbes have the potential to produce a broad range of distinctive nanostructures. This has increased researchers' curiosity about using these microorganisms and plants to generate nanostructures for a variety of purposes. By using bio-mediated and induced synthesis, bacteria and fungi may produce inorganic compounds (Moitra *et al.*, 2020). It is feasible to produce nanostructures with the appropriate geometries and structure by manipulating biological synthesis. The biological synthesis of nanoparticles is nevertheless restricted because of its particle geometry controllability and process scalability, irrespective precision of the nanoparticle physicochemical synthesis (Fang *et al.*, 2019). Yet, utilizing common metal precursors and a variety of compositions, physiologically induced synthesis has enabled researchers to generate inorganic nanoparticles (Grasso *et al*. 2019).

With increasing frequency, nanosized particles are produced by plants and microbes such as bacteria, algae, fungi and yeast. There are many distinct types of microorganisms, and they all react with metal precursors in somewhat various manners to generate nanoparticles. For instance, both intracellular and extracellular synthesis is possible in bacteria and fungi, and each of these processes has a unique mechanism in each kind of microorganism. The cell wall is used in intracellular synthesis to transport metal ions, where the positive-charged ions interact with the negative-charged wall. These ions are converted to metal nanoparticles in the cells by enzymes. The accumulation of metal ions on the cellular membrane and the activation of minimizing ions through enzymes are different aspects of the factors underlying the extracellular synthesis of nanoparticles (Mughal *et al.* 2021).

4.1. Synthesis of Plant-mediated Nanoparticles

Due to efficacy, feasibility, and energy efficiency, plant-mediated nanoparticle synthesis was beneficial (Mittal *et al*. 2013). Various plant parts like flowers, fruit, roots, leaves and stems, are used for synthesis (Herlekar *et al.* 2014), and this process is known as 'Green synthesis'. Plant extract contains proteins, polyphenols, enzymes, secondary metabolites, reducing agents, polysaccharides and electron shuttling, which helps synthesize and sustain a nanoparticle's stability (Rajeshkumar and Bharath, 2017). The mechanism involved in synthesizing plant-mediated nanoparticles is manifested in Fig. 3. The plant extract capping and stabilizing agents determined the nanoparticle’s size, shape and morphology. Though plants are abundant in phytochemicals such as sugars, polyphenols and ascorbic acid, plant-mediated synthesis is less-costly and eco-friendly and requires less time consumption when compared with microbe-mediated synthesis (Parsons *et al.* 2007).

According to some experts, the redox activity of every metal varies and has a significant impact on how metals or metal precursors are reduced throughout the synthesis. The metal precursor can be reduced more quickly if the favourable redox potential is higher. When the diminishing rate is lesser, the nucleation and growth phases will be very close to stability (Zhang *et al.* 2015). The slower reduction rate plays a significant role in the synthesis of Silver-Palladium core-shell nanoparticles in single-step biosynthesis. According to the research, the reduction potentials of $PdCl_2$/2Pd and $AuCl_4$/Au are 0.59 and 0.99 eV, correspondingly. Based on the TEM analysis, at various periods during the process, silver nanoparticles were generated before palladium nanoparticles. This is quite compatible with the reduction potential difference between $PdCl_4$/2Pd and $AuCl_4$/Au, and it is thought that this variance is crucial for the synthesis of core-shell nanoparticles (Khan *et al.* 2022).

Zero-valent iron nanoparticle (ZVI NP) consists of a wide surface area enclosed by two ions (sulfide and iron ions), thus strengthening adsorption capabilities. Biomolecules like polyphenols, amines, phenols and flavonoids which are found in the plant extract serve as reducing, capping, and stabilizing agents. *Phoenix dactylifera* zero-valent iron nanoparticle size was 68 nm *via* scanning electron microscope; crystalline growth in XRD and broad peaks were spotted between 1410 to 1625 cm^{-1} in FTIR. It has the propensity to degrade 97% of chromium and ciprofloxacin from wastewater (Thilakan *et al.* 2022). TEM analysis of eucalyptus leaves ZVI NP shows a spheroidal shape, and the presence of abundant biomolecules is responsible for the smooth surface with mash-like capping formation in the synthesized nanoparticle. FTIR results revealed the existence of biomolecules such as aliphatic amines and polyphenols; it shows 100% efficiency in removing chromium at 80 °C, and pH should be acidic (Liu *et al.* 2018). Owing to the polyphenols in tea extract, it helps to form a network with metal iron ion ($FeSO_4$), and then furtherly, the metal iron is reduced to make up a zero-valent metal. Those synthesized nanoparticles were introduced to the gamma radiation source with a dose of 7.5 kGh^{-1}, which resulted in flake-like aggregates. The width range lies between 0.1 – 0.17 µm and contains 97% efficiency in removing Cu (II) ions from wastewater (Amin *et al.* 2021).

Green mulberry and Oak leaf extract-mediated ZVI nanoparticles were more efficient in removing Cu and Ni in wastewater. SEM and TEM reported that the formed ZVI nanoparticles of green mulberry and oak leaf were globular in shape with minimum agglomeration, and their size lies between 10nm to 30 nm. The Freundlich model states that oak-mediated ZVI NP shows high removal capacity for Ni at 777 mg Ni/g at pH 8, and green mulberry-mediated ZVI NP removes Cu at 1,047 mg Cu/g at pH 7 (Poguberovic *et al.* 2016).

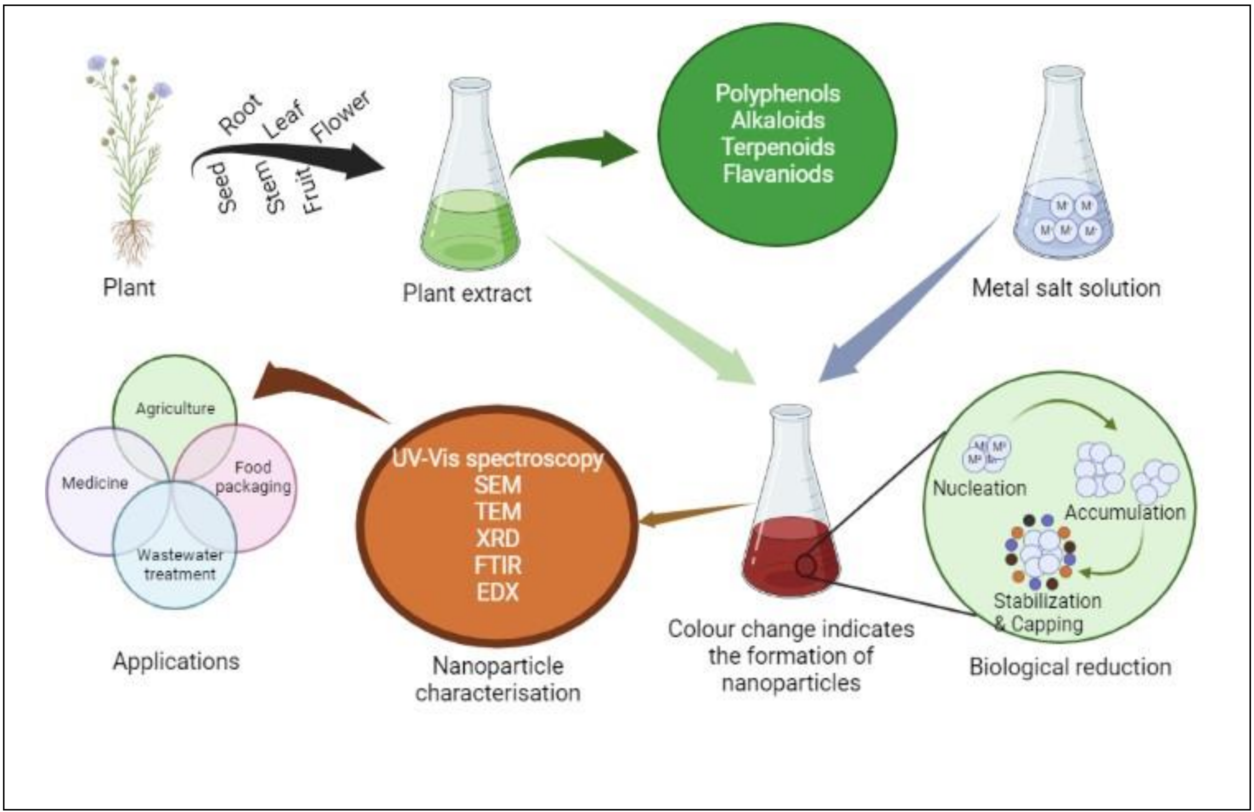


Fig. 3: Synthesis of plant-mediated nanoparticles

Fourier transform infrared (FTIR) analysis addresses the leaf extract of *Aloe vera* Fe_2O_3 nanoparticles exhibiting the activity of polysaccharides, anthraquinones, and amino acids like glycine and alanine act as bio-stabilizers. The synthesized *Aloe vera* Fe_2O_3 NPs adsorb the arsenic up to 38.47 $mg\text{-}g^{-1}$ (Mukherjee *et al.* 2016). Tea waste magnetic iron oxide synthesized nanoparticles size ranges from 5 to 25 nm showing the extreme adsorption of As (III) at 188.69 $mg\text{-}g^{-1}$ and As (V) at 153.8 $mg\text{-}g^{-1}$ (Lunge *et al.* 2014).

4.2. Synthesis of Microbes-mediated Nanoparticles

Nanotechnology combined with microorganisms produces an excellent initiative for wastewater treatment bioremediation of industrial contaminants and excludes heavy metal ions (Shukla, 2020). Bacterial and fungal enzymes serve as reductive agents for the metal complex salt and produce metallic nanoparticles (Mahanty *et al.* 2020). Microorganisms produce intracellular and extracellular enzymes which help to synthesize metallic nanoparticles. The active electrostatic interactions between the amide groups and metal cations found in the cell wall of microorganisms have the capacity to reduce the ions by the production of intracellular enzymes and thus induce the formation of metallic nanoparticles (Kapoor *et al.* 2021). Extracellular enzymes act as a reducing agent and help to form nanoparticles (Subbaiya *et al.*, 2017); some extracellular enzymes produced by fungal species such as glucosidase, acetyl xylan esterase, NADH and cellobiohydrolase D helps to synthesize the metallic nanoparticles (Ovais *et al.* 2018). Fig. 4 explains the synthesis of microbe-mediated nanoparticles *via* intracellular and extracellular matrices.

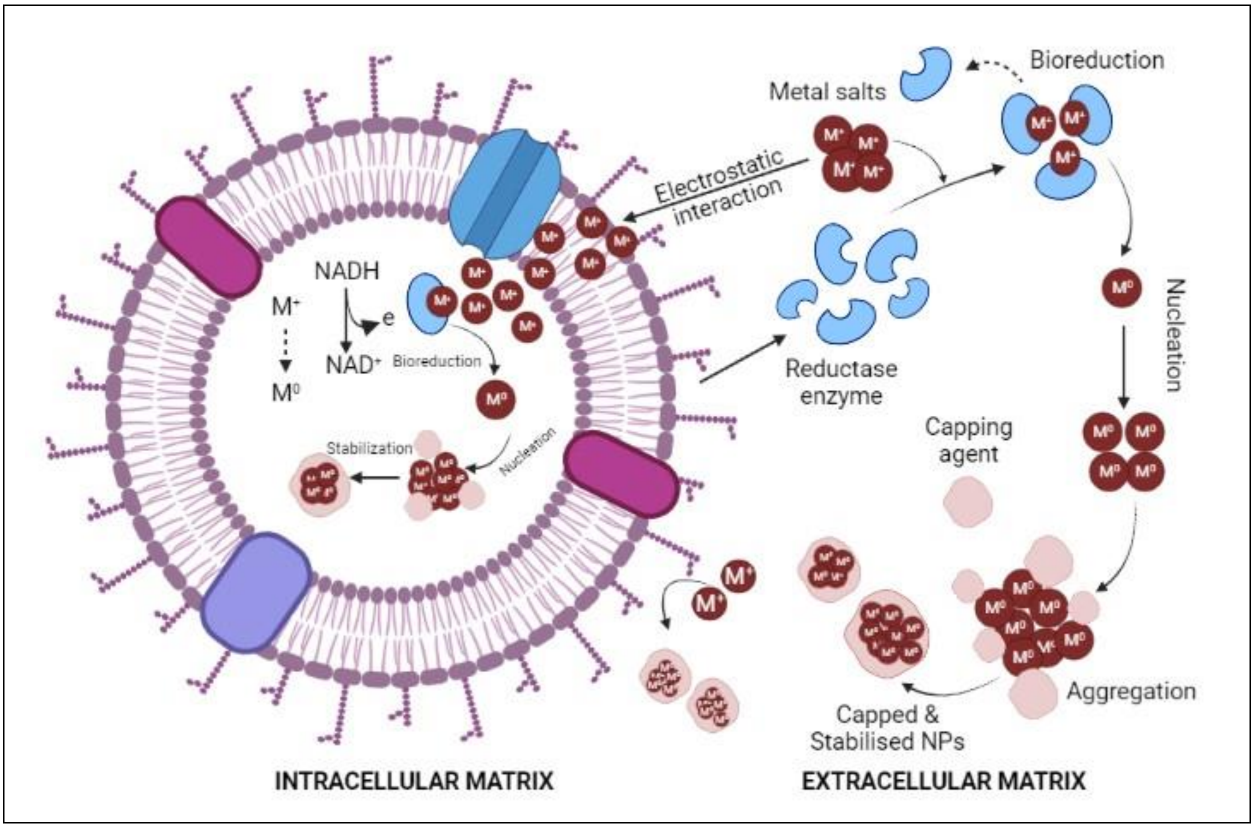


Fig. 4: Synthesis of microbe-mediated nanoparticles

4.2.1. Synthesis of Bacteria-mediated nanoparticles

Bacteria enact majorly in bioleaching, biomineralization and bioaccumulation. The oxidation or reduction process alters its oxidation state to solubilize the metal ions (Raĭkher *et al*. 2010). Bacteria can potentially reduce the toxic soluble inorganic ions into non-toxic insoluble metal nanoparticles. The synthesis takes place either intracellularly or extracellularly under specific physiochemical circumstances such as solution pH, the temperature of the solution, the amount of metal salts and bacterial load. In the extracellular process, the biomolecules found in the bacterial cell wall help to reduce the metal ions. In contrast, the functional groups in the bacterial cell wall attract the metal ions and merge with protein by electrostatic interaction in the intracellular process (Fang *et al.* 2019). The bacterial cell wall can arrest the metal ions due to their negatively charged group within its fabric. The method includes entrapment in extracellular capsules, complexation, biosorption to cell walls, oxidation/reduction and precipitation. Copper ions in wastewater are effectively removed by some bacterial species such as *Bacillus* sp., *Pseudomonas cepacian*, *Micrococcus lutues*, *Streptomyces lumanlinharesii*, *Streptomyces coelicolor*, *Bacillus subtilis*, *Arthrobacter nicotianae* and *Enterobacter* sp. (Agarwal and Singh, 2017).

Southam and Beveridge, recognized the first microbe-mediated gold nanoparticle using *Bacillus subtilis.* Bacterial species such as *P. aeruginosa* (Srivastava and Constanti, 2012), *B. megatherium* (Wen *et al*. 2008), *E. coli* (Du *et al*. 2007), *B. subtilis* (Sathiyanarayanan *et al*. 2013), *Staphylococcus aureus* (Nanda and Saravanan, 2009), *Lactobacillus* sp., (Prasad *et al.* 2007), *Enterobacter* sp., (Shahverdi *et al.* 2007) also actively participated in the formation of silver and gold nanoparticles. *E.coli* K12 mediated AuNPs exhibit the catalytic degradation of a 4-nitrophenol and nitroaromatic contaminant in water (Srivastava *et al.* 2013). *Bacillus cereus*-mediated silver nanoparticle shows effective antibacterial activity (Prakash *et al.* 2011). Cellulose acetate (CA) fibers-assisted silver nanoparticles and MgO nanoparticles using *Streptococcus* sp., possess antibacterial activity against spore-forming, Gram-positive, and Gram-negative bacteria (Savage and Diallo, 2005). *Pseudomonas aeruginosa* and *Pseudomonas stutzeri*-mediated iron nanoparticles can survive and degrade the heavy metal ions. Iron nanoparticles were synthesized using *Escherichia* sp., SINT7, a copper-resistant bacteria. The synthesized iron nanoparticles can degrade phosphate, chloride ions, suspended solid particles, azo dyes, and textile effluents like malachite green, black-5, direct blue-I and congo red (Noman *et al.* 2020).

Clostridium pasteurianum mediated palladium nanoparticles show positive remediation in the conversion of Cr (VI) to Cr (III), which results in the formation of hydrogen gas, and the removal rate of chromium is 7.2 g Cr (VI) (Chidambaram *et al*. 2010). *Lysinibacillus sphaericus* secretes exopolysaccharides which act as a reducing, capping and stabilizing agent. Magnetic oxide nanoparticles from *Lysinibacillus sphaericus* can degrade Cr (VI) ions from wastewater (Subramaniyam *et al*. 2015). *Bacillus cereus*-mediated silver nano adsorbents remove 98% of Cr and Pb from waste effluents. Immobilization of *Pseudomonas aeruginosa* on polyvinyl alcohol (PVA), carbon nanotube matrix, and sodium alginate results in the biological reduction of Cr (III) up to 84% within a day. Meanwhile, immobilization of *Shewanella aneidensis* on calcium alginate beads also decreases the level of noxious Cr (VI) into Cr (III) in wastewater (Yan *et al.* 2013).

4.2.2 Synthesis of fungi-mediated nanoparticles

Fungal species are ubiquitous in nature; it contains the maximum level of metal tolerance and the capability to concentrate the metal ions in them (Dhillon *et al.* 2012). The fungal mycelium secretes proteins because it contains a large surface area that helps synthesize the nanoparticles efficiently *(Mohanpuria et al*. 2008). Distinctive fungal species have their mechanism for their growth and nanoparticle synthesis (Fouda *et al.* 2018). Synthesis, stabilization and immobilization were carried out by secreting various enzymes, polypeptides, proteins and other metabolic interactions, which also maintains and preserves their propensities as nanocatalysts and nano-adsorbents (Yadav *et al*. 2015).

Fungi synthesize nanoparticles intra/extracellularly, just like other microorganisms do. The microbe produces a large number of tiny nanoparticles that are produced elsewhere in the environment. The size constraint is connected to species-specific particle nucleation. Intracellular synthesis also offers several significant advantages. Diminished metals including copper and platinum should be eradicated from the ecosystem to remedy the consequences of ecological degradation. Fungi that generate intracellularly would be perfect to utilize due to their ability to remove the pollutants from the sample (Crane *et al*. 2011). As nanoparticles are produced outside of cells, they frequently have a broad range of practical applications. Due to their ability to sequester nanoparticles through a variety of secreted chemicals, fungi are frequently thought of as extracellular species. Extracellular synthesis is more straightforward and relatively inexpensive.

Extracellular gold nanoparticles were synthesized by using *Fusarium oxysporum*. Due to its protein binding capacity property, it maintains the prolonged fastness of the synthesized gold nanoparticles (Das *et al*. 2017). *Cladosporium resinae*, *Aureobasidium pullulans*, *Trametes versicolor*, *Aspergillus niger*, *Rhizopus arrhizus*, *Funalia trogii*, *Ganoderma lucidum*, and *Penicillium* species also eliminate the heavy metal ions (Say *et al*. 2003). *Aspergillus tubigensis* (STSP. 25) - mediated iron oxide nanoparticles can remove 90% of toxic metals like As, Cu, Ni, Pb and Zn in the wastewater. The fungal species is identified from the rhizosphere soil of *Avicennia officinalis.* Due to the endothermic reaction of *Avicennia officinalis*, the metal ions are chemically fascinated on the nanoparticle shell (Mahanty *et al*. 2020). *A. japonicus* APJ01 synthesized 'nanogold-fungal composite' can decrease the level of Au (III) to Au, immobilize the silver nanoparticles, and increase the $NaBH_4$ associated catalytic reduction of hexacyanoferrate (III) and 4-nitrophenol (Bhargava *et al*. 2015).

Hulikere & Joshi, revealed that *Cladosporium cladosporioides* have the ability to produce silver nanoparticles with widths ranging from 30 to 60 nm. In FE-SEM pictures (Noor *et al.* 2020), AgNPs had a consistent size and spherical morphology. Fungal species including *Gliomastix murorum*, *Cladosporium cladosporioides*, and *Agaricus bisporus* are known for aggressively removing copper ions from their environments (Agarwal and Singh, 2017). The biosynthesis of *Hypocrea lixii* nickel oxide nanoparticles actively eliminates the nickel ions present in wastewater (Torimiro *et al.* 2021). *Fusarium oxysporum* secretes enzymes like anthraquinones and nitrate reductase, which help synthesize a silver nanoparticle. It clearly shows that the NADPH nitrate reductase enzyme plays a significant part in synthesizing metallic nanoparticles (Durán *et al*. 2005).

Nanomaterials are employed to eliminate radioactive contaminants and hazardous metals due to their wide (and rapid) surface area-to-volume ratio (Ding *et al*. 2019). For this desired purpose, magnetite NPs are more effective than other metal nanoparticles due to their superparamagnetic nature, which makes it simple for them to be isolated from wastewater by electrostatic and surface complexation.

4.2.3 Synthesis of Yeast-mediated nanoparticles

Yeast cells are also known as semiconductor crystals, and their detoxification mechanism is carried out by phytochelatins, glutathione, and metallothioneins (Grasso *et al*. 2019). *Pichia jadiniii*-mediated gold nanoparticles exhibit high stability because it contains peptide coating which does not allow the particles to aggregate (Koul *et al*. 2021). Metals and hydrocarbons were actively removed by *Yarrowia lipolytica*-mediated metallic nanoparticles (Bankar *et al*. 2009). *Saccharomyces cerevisiae, Candida glabrata, Schizosaccharomyces pombe, Candida albicans,* *Candida utilis, Rhodotorula mucilaginosa, Trichoderma koningiopsis* and *Hypocre lixii* also eliminate the heavy metal ions (Kapoor *et al*. 2021). In *Yeast lipolytica* NCIM 3589 and NCIM 3590-mediated iron nanoparticles, the nanocomposites were poly-dispersed, crystalline and the maximum adsorption of chromium up to 125 and 156.3 mg-g^{-1} (Rao *et al*. 2013). Beer yeast is less expensive and excellent sorbent to remove copper ions from wastewater (Agarwal and Singh, 2017).

4.2.4 Synthesis of Algae-mediated nanoparticles

Algae are photoautotrophic and abundant in bioactive compounds like hydroxyl, carboxyl and amino functional groups, which assist as both capping and reducing agents for the synthesis of nanoparticles (Shankar *et al.* 2016). Typically, an algae-mediated nanoparticle synthesizing procedure entails the following steps: (1) preparing algae isolates in liquid at an increased temperature; (2) preparing chemicals and (3) gestating algae and reagent mixtures before agitating for a pre-determined amount of period (Sharma *et al.* 2016). The metal precursor and algal extract are combined to begin the reaction. An alteration in color indicates the initiation of a process that depicts nucleations, accompanied by the formation of nanoparticles where the neighboring nucleonic particles unite and generate thermodynamically stable nanoparticles of varied shapes (Kumaresan *et al*. 2018). The primary parameters include temperature, period, pH, and concentration, and the extracted bio-compounds to enhance the production of nanoparticles.

Marine algae such as brown algae, red algae, and cyanobacteria (green algae) can remove copper ions from wastewater because they possess low cost, high capacity, ready abundance, and renewability; also, the cell walls of the algae have strong biosorption. Green algae, such as *Ulothrix zonata*, *Spirulina platensis*, *Spirogyra neglecta* and brown algae, such as *Turbinaria ornate*, play a vital role in eliminating copper from wastewater (Agarwal and Singh, 2017). HPLC analysis of *Chlorella vulgaris*-mediated gold nanoparticles show the protein is present, and its molecular weight is 28 kDa, which is responsible for reducing and stabilizing nanoparticles. *C. pyrenoidosa* mediated gold nanoparticle acts as a nanocatalyst for the growth inhibitors for bacterial pathogens like *Klebsiella pneumoniae*, *Staphylococcus aureus*, *Acinetobacter* sp, and *A. hydrophilia;* also degrades the methylene blue dye (Edison *et al.* 2016). FTIR analysis of *P. oedogonia* aqueous extract-mediated gold nanoparticles report the presence of bioactive compounds such as steroids, proteins, amino acids, carbohydrates, saponins, and tannins which acts as a capping, reducing, and stabilizing agent for nanoparticles (Gautam *et al*. 2019). *Chlorella vulgaris*-mediated iron oxide nanoparticles eliminate 90 - 91% of PO_4^{3-} and 80 - 85% of NH_4^+ in wastewater (Govarthanan et al. 2020).

Shen *et al.* reported *Synechocystis* sp.-associated iron nanoparticles reveal a reverse relationship between the crystallinity of nanoparticles and the reaction temperature through X-ray diffraction. SEM and TEM images observed the aggregation of synthesized iron nanoparticles, which actively eliminates the Pb (II) when the pH level is at 2. *Chlorococcum* sp.-mediated iron nanoparticles reduce the level up to 92% of Chromium (VI) to Chromium (III). *Chlorella vulgaris*-mediated iron nanoparticles were characterized by EDX, FTIR, TEM, SEM, XRD, and XPS. Pb was aggregated on the superficial layer.

Meanwhile, Cd was absorbed to a significant scale at lower pressure. This process reveals that the sorption of Pb and Cd coincides. The functional emulsion of iron particles was validated by EDX analysis (Gupta and Nayak, 2012). The release of biomolecules from *Chlorella vulgaris* increases the photocatalytic reduction of Cr (VI) on TiO_2-mediated nanoparticles (Kumari and Tripathi, 2020).

4.2.5 Synthesis of Actinomycetes-mediated nanoparticles

Actinomycetes contain a vast surface area, and they produce secondary metabolites. Effective gold nanoparticles are produced by *Thermoactinomyces sp., Nocardia farcinica, Streptomyces hygroscopicus, Streptomyces viridogens, Rhodococcus sp., Thermomonospora* species, etc. (Składanowski *et al.* 2017). *Streptomyces* species are majorly acclimated to synthesize manganese, copper, iron, zinc and silver nanoparticles (El-Gamal *et al*. 2018). Actinomycetes-mediated nanoparticles actively degrade toxic metals such as copper, cadmium, nickel, lead, etc. Fig. 5, represents the mechanism carried out by the different types of microbes, such as bacteria, fungi, yeast, algae, etc., involved in nanoparticle synthesis.

5. APPLICATION IN WASTEWATER TREATMENT

Nanomaterials enclose a maximum sensitivity, reactivity, excess surface-to-volume ratio and large surface assimilation capacity, making them acceptable for applications in wastewater treatment. Bio-mediated nanoparticles have a higher efficiency rate of antimicrobial activity like antibacterial, antifungal, anticancer, larvicidal, etc. So, it actively kills the growth of pathogens and also contains antioxidant activity. Titanium-based nanoparticles efficiently remove arsenic from wastewater and drinking water (Ersan *et al.* 2017). Carbon and magnetic iron nanoparticles are sensors to detect pollutants from wastewater because of their prominent physiochemical and electrical properties (Kumar *et al.* 2018). Silver-mediated ceramic water nano-filters are used to eliminate various pathogens in water that causes the severe infectious disease to us (Pandey *et al.* 2017). Metal oxide nanoparticles contain strong catalytic reactivity toward environmental pollutants. TiO_2 photocatalyst can remove various impurities from wastewater (Soppe *et al.* 2015). Biological compounds mediated zero-valent nanoparticles like zinc, iron, silver and metal oxide nanoparticles like copper oxide, zinc oxide, iron oxide and titanium oxide, and prominently removed the metal ions from the wastewater. Various nano-cellulose materials are accessible for water purification systems, such as cellulose nanocrystals (CNC) and cellulose nanofibrils (CNF). Nanoparticles are currently found in market areas as adsorption layers, biosorption layers, nanocatalysts, nano photocatalysts, nanomembranes, etc., serving as an easy-to-handle and affordable product.

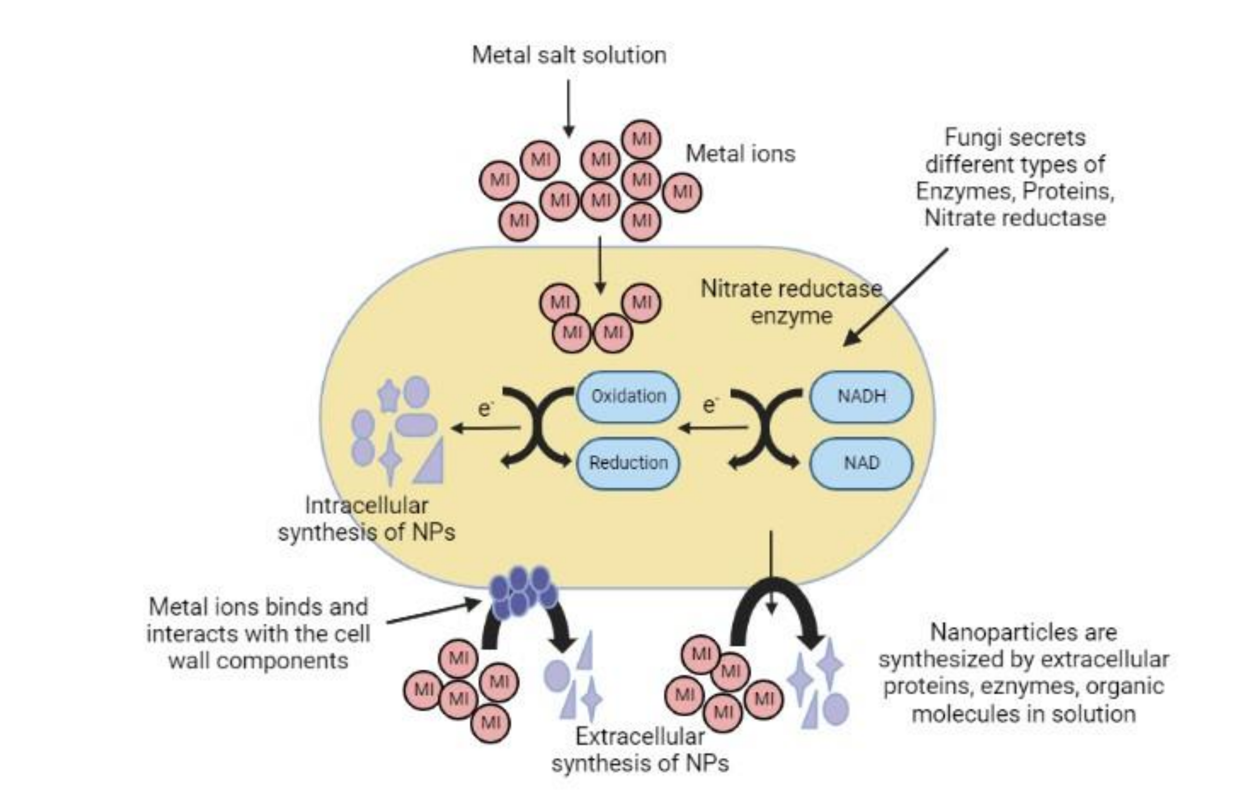


Fig. 5: Synthesis of nanoparticles by using microorganisms such as bacteria, fungi, algae, yeast, actinomycetes, etc.

5.1. Adsorption

Sorption is a technique in which the ions present in the liquid phase are transferred to the solid phase, and it is categorized into two groups: adsorption and precipitation reactions. Adsorption is a complex method in which a huge compound passes from a liquid to a solid. This technique is widely used to degrade the toxic metal ions present in wastewater in three main steps, the pollutants present in the mass solution are transferred to the sorbent's superficial layer; adsorption takes place on the particle shell; transfer within the sorbent particle (Barakat, 2011).

Currently, heavy metal-contaminated effluent has been cleaned up using carbon nanotubes (CNTs). Carbon nanotubes come in two primary varieties: single-walled and multi-walled. Because of their quick adsorption kinetics, large definite surface area, and maximum adsorption capacity—which are especially pronounced in toxic metal ions including Mn^{7+}, Ti^{+}, Cu^{2+}, Pb^{2+} and Cr^{7+}—CNTs are capable of handling heavy metal wastewater significantly more effective than traditional therapeutic approaches (Yadav and Srivastava, 2017). In order to enhance the adsorption capabilities of CNT surfaces assisting toxic metals, functional groups like -COOH, -NH and -OH may be added *via* thermal processing, chemical modification or endohedral filling (Kumar *et al*. 2021).

Shewanella oneidensis-immobilized cells that were substantial with CNTs also demonstrated a potential bio-functionalized activity that led to the biotransformation of hazardous Chromium (VI) to Chromium (III) (Yan *et al*. 2013). In comparison to the combined effects of the test bacteria and calcium alginate beads, the immobilizing/inactivating substance (calcium alginate), *S. oneidensis* and CNTs were reported to be four times more efficient in decreasing hexavalent chromium. In order to cope with settings affected by inorganic contaminants, our research shows that the combination of CNTs with bacteria may improve nano-bioremediation processes. Because of their vast surface area, raised reactivity, controllable effects, precise magnetic properties, potent reducing power, and capacity to adsorb a variety of toxic metals and metalloids, magnetic iron oxide nanoparticles (MIONPs), among other nanomaterials revealed so far, are broadly used in the discharge of metal (Shin *et al*. 2016).

By converting chromium (VI) to an immobile trivalent state and releasing hydrogen gas, palladium (Pd) nanoparticles from Pd (II) ions facilitated by *Clostridium pasteurianum* have shown considerable bioremediation of both mutagenic and carcinogenic chromium (Alexakis, 2016). *Pseudomonas aeruginosa*, polyvinyl alcohol (PVA), and sodium alginate coated CNTs matrix have also been shown to selectively detoxify Cr (VI). At 80 mg/L Cr (VI), the inactivated bacterial cells have the capacity to reduce Cr (VI) by 84% furtherly; it is responsible for soluble Cr (III), however, totally it is eliminated within 24 hours (Pang *et al.* 2011).

5.2. Biosorption

Removing heavy metals from wastewater using biosorption with bio-reduction is an effective method. Depending upon the pH, algal-bacterial aerobic granular sludge can remove chromium (VI) from wastewater (Yang *et al*. 2020). Alginate-immobilized *Aspergillus niger* microsphere is an active biosorbent that removes Thorium (Th) ions in radioactive wastewater (Ding *et al.* 2019).

Mercury and selenium combine to produce HgSe, a non-toxic molecule that is less hazardous than mercury and selenium separately. Moreover, under both aerobic and anaerobic circumstances, nano-selenium can intrigue mercury. Remediation of mercury-contaminated soils can be accomplished by immobilizing the metal using nano-selenium (Hidangmayum *et al*. 2022).

Exopolysaccharides (EPS), a crosslinking, stabilizing, and encapsulating agent, were found to be secreted by *Lysinibacillus sphaericus* while making magnetic oxide nanoparticles. EPS has many binding sites for different metal ions (Kumar *et al.* 2019). An improved capacity for absorbing Cr is present in the EPS bifunctional magnetic oxide nanoparticles (VI).

In a further investigation, it was discovered that chitosan nanoparticles (NCt), which were biosynthesized from *Cunninghamella elegans* utilizing a bioactive polymer (chitosan), had greater biosorption and, as a result, greater bioremediation efficacy against Pb (II) and Cu (II) ions than bulk chitosan (Alsharari *et al.* 2018).

5.3 Nanocatalysts

Nanocatalysts contain a high surface area with a shape-dependent property. So, it induces surface catalytic activity and enhances reactivity; it is actively involved in contaminating contaminants in wastewater. Environmental pollutants include Polychlorinated Biphenyls (PCBs), nitro aromatics, halogenated herbicides, aliphatic, azo dyes and organochlorine pesticides are degraded by the most frequently used catalytic nanoparticles such as semiconductors, bimetallic nanoparticles, zero-valence metal, metal oxide nanoparticles, etc (Zhao *et al.* 2011).

Currently, researchers focused on the remediation of toxic metals by using a variety of nanocatalysts that are produced by microbes (Roy *et al.* 2021). Small molecule adsorbates were made in large part using Ag nanoparticles as optical sensors. A substantial reaction rate for the electro-oxidation of formic acid was discovered for Pt nanoparticle-based catalysts (Amin *et al*. 2021).

Ha *et al.*, discovered *Enterococcus faecalis* was used to make palladium nanoparticles, which were then used to remove hexavalent chromium from polluted waters. *Aspergillus tubingensis*-derived iron oxide nanoparticles were identified as having a significant capacity for regeneration and to be the ability to extract toxic metals from wastewater, including lead 98%, nickel 96%, zinc 94% and copper 92% (Mahanty *et al.* 2020).

In plenty of other studies, the combined treatment of *B. subtilis* and nanohydroxyapatite effectively eliminated Cd from a Cd-contaminated ecosphere, as did the polymer-assisted production of CdS nanocatalysts made from the *Pseudomonas aeruginosa* (Gram-negative bacteria) (Raj *et al.* 2016).

Rhodosporidium diobovatum yeast was used to generate the lead sulfide (PbS) nanocatalysts, which were then used to bio-transform the hazardous Pb (II) ions into minimal hazardous and beneficial forms (Seshadri *et al.* 2011).

5.4 Nano-photocatalysts

Nano-photocatalyst, the substances are induced by light (UV, visible and sunlight). It is more commonly used to purify wastewater because they possess an elevated superficial ratio and shape progeny characters, which helps to enhance the catalyst reactivity (Chen *et al.* 2019). TiO_2-based nanotubes act as an effective photocatalyst to remove wastewater contaminants (Yamakata and Vequizo, 2019).

In order to properly remediate acidic water contaminated with toxic metals, zero-valent iron nanoparticles seemed to solubilize the toxic metal pollutants on their interaction. This makes them a feasible and essential method of nano-remediation *(Saif et al*. 2016). Zinc nanoparticles were thoroughly explored and investigated by experts from every part of the globe due to their extraordinary capacity to degrade organic dyes. Zinc nanoparticles are semiconductor photocatalysts that have the ability to destroy different types of substances, such as dyes, medicines, and phenols (El-Kemary *et al.* 2010).

Chlorella vulgaris has been incorporated as a bifunctional agent in ultrafine bi-metallic (TiO_2/Ag) chitosan nanofiber mats, thereby highlighting the importance of algae in the detoxification of cancer-causing chromium (Wang *et al*. 2017). The photocatalytic degradation of hexavalent chromium on TiO_2/Ag chitosan nanofiber mats was found to be considerably enhanced by the excretion of various organic compounds by *C. vulgaris*, including chlorophylls and carboxylate acids. As a result, it was determined from this research that the interaction between algae and the TiO_2/Ag hybrid nanocomposites may become beneficial in eliminating chromium from a contaminated site at a reasonable cost (Saleem *et al.* 2022).

5.5 Nanomembranes

The membrane comprises various nanofibers, effectively removing unwanted nanoparticles in the liquid phase. It is widely used in reverse osmosis in the pre-treatment method to purify the wastewater because it has a very high removal speed and condensed fouling propensity (Jhaveri and Murthy, 2016). Commonly, biogenic nanoparticles are made into nanomaterials and actively participate in an antimicrobial activity such as antibacterial, antifungal and antiviral; it eliminates biofilm production (Saleh *et al.* 2019). Nanomaterials are broadly used to treat wastewater because they possess more productivity, high uniformity, less period, optimization, homogeneity and ease of handling (Gopalakrishnan *et al.* 2018).

Zirconium oxide bio-nanocomposite has been demonstrated to function optimally at pH = 5, contact time of 180 min, starting concentration of 100 (ppm), and dose of 0.1 g sorbent. The findings indicate that the sorption technique is best explained by the Langmuir and the first pseudo-order with R2 value (biomass=0.99; biochar=0.99; ZrO2BNC=0.99) (Hussain *et al.* 2022).

The CuO/rGO nanocomposite had a 98% and 90% removal efficiency for Bi^{3+} and Cd^{2+} ions, correspondingly. Pure CuO and rGO were also employed for eliminating metal ions from the process in similar circumstances. When compared to pure CuO and rGO, it was shown that the elimination effectiveness of the CuO/rGO nanocomposite was significantly higher. As a result, the concentration of CuO nanoparticles in the CuO/rGO nanocomposite was primarily blamed for the adsorption of Bi^{3+} and Cd^{2+} ions (Kumari *et al*. 2022).

In order to eliminate lead and arsenic ions from wastewater, Alswata *et al.*, used the ZnO/Zeolite nanocomposite. At pH 4, 0.15 g, and 30 min, the greatest adsorption rates of lead and arsenic ions were 93% and 89%, correspondingly.

The latest research has shown that the biologically active approach of nanocomposite production using *Citrobacter freundii* Y9 is successful in removing Hg-polluted soil (Wang *et al*. 2017).

As an adsorbent that facilitates the elimination of Pb^{2+} and Cd^{2+} ions from wastewater, Kumar *et al.*, designed the formation, characterization and application of ZnO-NiO-based nanocomposite. For this compound, the adsorption efficiency was found to be 1519.7 mg^{-1}. The pseudo-second-order kinetic model showed that the adsorption process displayed chemisorption.

5.6 Nanosorbents

Nanosorbents are carbon-based compounds that actively participate in water purification, treatment, and remediation because of their specific and high sorption capacity (Yaqoob *et al.* 2020). Different nanosorbents are regenerable polymeric nanosorbents, nano-clays, carbon-iron, and nanonetworks. Magnetic nanosorbents can treat wastewater because they can degrade the organic contaminants such as dyes, surfactants and phenolic compounds, present in wastewater (Campos *et al.* 2011). Even metal oxide and polymeric nanosorbents are used to treat wastewater (Yu *et al.* 2017). Materials like Ag/polyaniline, C/TiO_2, and Ag/carbon may reduce the toxic effects during wastewater treatment. Dendrimers are polymeric nanosorbents that actively eliminate toxic metal ions and organic contaminants from wastewater, including dyes, pesticides, etc (Fuwad *et al.* 2019). Carbon-based nanosorbents actively eliminate Ni ions (Rodovalho *et al.* 2016); nano-aerogels are for uranium (Krstic *et al.* 2018); polymeric fibers are for arsenic (Yadav *et al.* 2019) and nano-metal oxide is used to degrade various toxic metal ions present in wastewater (Wang *et al.* 2016).

A current research investigation showed the potential for producing iron nanoparticles from biological communities, it may absorb chromium, arsenic, zinc and copper from effluent (Castro *et al.*, 2018). With the aid of the soil bacteria *Pseudomonas* sp. QJX-1 isolated from manganese mines, biogenic Fe-Mn oxides (BFMO) production was accomplished. Arsenic was discovered to be oxidized and adsorbed by these oxides. This enables sufficient adsorption and oxidation of As(III) and As(V) (Bai *et al.* 2016). It has also been established that chromium-containing wastewater could be treated by using sulfate-reducing bacteria (SRB). SRB has the capacity to eliminate sulfate and COD from wastewater, organic molecules must be present as a carbon source. Investigations on simulated wastewater beneath optimal circumstances developed the removal efficiency of up to 95.3% of sulfate, 89.2% of Cr^{7+} and 81.9% of COD (Verma *et al.* 2015).

Pseudomonas putida MnB1 mediated biologically active manganese oxide (BMO) have the capacity to eliminate the toxic metal ions present in the atmosphere. When contrasted to chemically produced manganese oxide, BMO has demonstrated higher effectiveness in the adsorption of toxic metal ions. BMO is a great adsorbent because of its amorphous nature, compact size, and substantial surface area. BMO adsorbs lead, cadmium, and zinc at a rate that C 7-8 times more than that of birnessite, while when there are alterations in temperature and pH, BMO adsorbs toxic metals much more effectively (Zhou *et al.* 2015).

Green algae *Chlorococcum* sp.-mediated iron exhibits strong reactivity, better stability and an effective reducing capacity, significantly decreasing the Cr (VI) to Cr (III) by 92% (Subramaniyam *et al.* 2015).

6. CONCLUSION

Nano-bioremediation is a promising technology that is sustainable, low-cost, feasible and eco-friendly to treat contaminants and eliminate environmental pollutants such as toxic metal ions, dyes, and biotic and abiotic contaminants by using microbe-mediated nanoparticles from wastewater. This method enhances the advancement rate and actively eliminates the chemical and chemical-free pollutants present in wastewater. Also, it has high efficiency because the particle size is small. The important property of biogenic nanoparticles is their high-efficiency rate of antimicrobial properties because they contain more polysaccharides, enzymes, proteins, flavonoids, etc. Bio-mediated nanoparticles may actively exterminate the toxic metal ions, such as arsenic, mercury, cobalt, nickel, copper, lead, manganese, cadmium, etc., from the wastewater, which is commonly harmful to humans and the ecosystem. The synthesized bio-mediated nanoparticles are used in a granule/powder form during wastewater treatment. They may also be used in nanomaterials, nanosorbents, nanofibers, nanomembranes and nanocatalysts, which are economical, less-energy, less-period, eco-friendly and highly efficient techniques. The biological substance consists of plants like roots, leaves and stems and microorganisms such as bacteria, fungi and yeast. They are arrested by metallic ions such as silver, gold, titanium, etc. So, it is impossible to cause any infectious disease in humans and other environments. Bio-mediated zero-valent and metal oxide nanoparticles tend to exclude metal ions in wastewater systematically. Recently, researchers found that bio-mediated nanoparticles are extensively used in wastewater treatment to effectively degrade chemical and chemical-free pollutants without causing any toxic effect on human beings and surrounding environments; the cost of commercialization, required period and energy consumption are also substantially lesser than other techniques.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Agarwal, M., and Singh, K., Heavy metal removal from wastewater using various adsorbents: a review, *J. Water Reuse Desalin.*, *7*(4), 387–419 (2017). https://doi.org/10.2166/wrd.2016.104

Akpor, O. B., Wastewater effluent discharge: Effects and treatment processes, In 3rd *International Conference on Chemical, Biological and Environmental Engineering IPCBEE*, *IACSIT Press*, 20, (2021).

Alexakis, D., Human health risk assessment associated with Co, Cr, Mn, Ni, and V contents in agricultural soils from a Mediterranean site, *Arch. Agron. Soil Sci.*, *62*(3), 359–373 (2016). https://doi.org/10.1080/03650340.2015.1062088

Alsharari, S., Tayel, A., and Moussa, S., Soil emendation with nano-fungal chitosan for heavy metals biosorption, *Int. J. Biol. Macromol.*, *118*, 2265–2268 (2018). https://doi.org/10.1016/j.ijbiomac.2018.07.103

Alswata, A., Ahmad, M., Al-Hada, N., Kamari, H., Hussein, M., and Ibrahim, N, Preparation of zeolite/zinc oxide nanocomposites for toxic metals removal from water, *Results Phys.*, *7*, 723–731 (2017). https://doi.org/10.1016/j.rinp.2017.01.036

Amin, R., Mahmoud, R., Gadelhak, Y., and El-Ela, F., Gamma irradiated green synthesized zero valent iron nanoparticles as promising antibacterial agents and heavy metal nano-adsorbents, *Environ. Nanotechnol. Monit. Manage.*, *16*, (2021). https://doi.org/10.1016/j.enmm.2021.100461

Babu, P. J., Sharma, P., Kalita, M. C., and Bora, U., Green synthesis of biocompatible gold nanoparticles using Fagopyrum esculentum leaf extract, *Front. Mater. Sci.*, *5*(4), 379–387 (2011). https://doi.org/10.1007/S11706-011-0153-1

Bai, Y., Yang, T., Liang, J., and Qu, J., The role of biogenic Fe-Mn oxides formed in situ for arsenic oxidation and adsorption in aquatic ecosystems, *Water Res.*, *98*, 119–127 (2016). https://doi.org/10.1016/j.watres.2016.03.068

Balamurugan, M., Saravanan, S., and Soga, T., Synthesis of iron oxide nanoparticles by using Eucalyptus globulus plant extract, *e-J. Surf. Sci. Nanotechnol*, *12*, 363–367 (2014). https://doi.org/10.1380/ejssnt.2014.363

Bankar, A. V., Kumar, A. R., and Zinjarde, S. S., Environmental and industrial applications of Yarrowia lipolytica, *Appl. Microbiol. Biotechnol.*, *84*(5), 847–865 (2009). https://doi.org/10.1007/S00253-009-2156-8

Barakat, M., New trends in removing heavy metals from industrial wastewater, *Arabian J. Chem.*, *4*(4), 361–377 (2011). https://doi.org/10.1016/j.arabjc.2010.07.019

Baruah, A., Chaudhary, V., Malik, R., and Tomer, V., Nanotechnology based solutions for wastewater treatment, *In Nanotechnology in Water and Wastewater*, 337–368 (2019). https://doi.org/10.1016/B978-0-12-813902-8.00017-4

Benazir, J., Suganthi, R., Rajvel, D., Pooja, M., and Mathithumilan, B., Bioremediation of chromium in tannery effluent by microbial consortia, *African Journal of Biotechnology*, *9*(21), 3140–3143 (2010).

Bhargava, A., Jain, N., Gangopadhyay, S., and Panwar, J., Development of gold nanoparticle-fungal hybrid based heterogeneous interface for catalytic applications, *Process Biochem.*, *50*(8), 1293–1300 (2015). https://doi.org/10.1016/j.procbio.2015.04.012

Campos, A. F. C., Aquino, R., Cotta, T. A. P. G., Tourinho, F. A., and Depeyrot, J., Using speciation diagrams to improve synthesis of magnetic nanosorbents for environmental applications, *Bull. Mater. Sci.*, *34*(7), 1357–1361 (2011). https://doi.org/10.1007/S12034-011-0328-5

Castro, L., Blázquez, M., González, F., Munoz, J., & Ballester, A., Heavy metal adsorption using biogenic iron compounds, *Hydrometallurgy*, *179*, 44–51 (2018). https://doi.org/10.1016/j.hydromet.2018.05.029

Chen, W., Liu, Q., Tian, S., and Zhao, X., Exposed facet dependent stability of ZnO micro/nano crystals as a photocatalyst, *Appl. Surf. Sci.*, *470*, 807–816 (2019). https://doi.org/10.1016/j.apsusc.2018.11.206

Chidambaram, D., Hennebel, T., Taghavi, S., Mast, J., Boon, N., Verstraete, W., and Fitts, J., Concomitant microbial generation of palladium nanoparticles and hydrogen to immobilize chromate, *Environ. Sci. Technol.*, *44*(19), 7635–7640 (2010). https://doi.org/10.1021/es101559r

Crane, R., Dickinson, M., Popescu, I., and Scott, T., Magnetite and zero-valent iron nanoparticles for the remediation of uranium contaminated environmental water, *Water Res.*, *45*(9), 2931–2942 (2011). https://doi.org/10.1016/j.watres.2011.03.012

Das, R. K., Pachapur, V. L., Lonappan, L., Naghdi, M., Pulicharla, R., Maiti, S., Cledon, M., Dalila, L. M. A., Sarma, S. J., and Brar, S. K., Biological synthesis of metallic nanoparticles: plants, animals and microbial aspects, *Nanotechnol. Environ. Eng.*, *2*(1), 1-21 (2017). https://doi.org/10.1007/S41204-017-0029-4

Debnath, B., Majumdar, M., Bhowmik, K., Debnath, A., & Roy, D., The effective adsorption of tetracycline onto zirconia nanoparticles synthesized by novel microbial green technologym, *J. Environ. Manage.*, *261*, 1-13 (2020). https://doi.org/10.1016/j.jenvman.2020.110235

Deplanche, K., and Macaskie, L. E., Biorecovery of gold by Escherichia coli and Desulfovibrio desulfuricans, *Biotechnol. Bioeng.*, *99*(5), 1055–1064 (2008). https://doi.org/10.1002/BIT.21688

Dhillon, G. S., Brar, S. K., Kaur, S., and Verma, M., Green approach for nanoparticle biosynthesis by fungi: Current trends and applications, *Crit. Rev. Biotechnol.*, *32*(1), 49–73 (2012). https://doi.org/10.3109/07388551.2010.550568

Ding, H., Luo, X., Zhang, X., and Yang, H., Alginate-immobilized Aspergillus niger: Characterization and biosorption removal of thorium ions from radioactive wastewater, *Colloids Surf., A*, *562*, 186–195 (2019). https://doi.org/10.1016/j.colsurfa.2018.11.032

Du, L., Jiang, H., Liu, X., and Wang, E., Biosynthesis of gold nanoparticles assisted by Escherichia coli DH5α and its application on direct electrochemistry of hemoglobin, *Electrochem. Commun.*, *9*(5), 1165–1170 (2007). https://doi.org/10.1016/j.elecom.2007.01.007

Durán, N., Marcato, P. D., Alves, O. L., De Souza, G. I. H., and Esposito, E., Mechanistic aspects of biosynthesis of silver nanoparticles by several Fusarium oxysporum strains, *J. Nanobiotechnol.*, *3*, 1–17 (2005). https://doi.org/10.1186/1477-3155-3-8

Edison, T. N. J. I., Atchudan, R., Kamal, C., and Lee, Y. R., Caulerpa racemosa: a marine green alga for eco-friendly synthesis of silver nanoparticles and its catalytic degradation of methylene blue, *Bioprocess. Biosyst. Eng.*, *39*(9), 1401–1408 (2016). https://doi.org/10.1007/S00449-016-1616-7

El-Gamal, M., Salem, S., and Abdo, A., Biosynthesis, characterization, and antimicrobial activities of silver nanoparticles synthesized by endophytic Streptomyces sp., *J. Biotechnol.*, *56*, 69–85 (2018). https://doi.org/10.1007/s00449-014-1205-6

El-Kemary, M., El-Shamy, H., & El-Mehasseb, I., Photocatalytic degradation of ciprofloxacin drug in water using ZnO nanoparticles, *J. Lumin.*, *130*(12), 2327–2331 (2010). https://doi.org/10.1016/j.jlumin.2010.07.013

Ersan, G., Apul, O., Perreault, F., and Karanfil, T., Adsorption of organic contaminants by graphene nanosheets: A review, *Water Res.*, *126*, 385–398 (2017). https://doi.org/10.1016/j.watres.2017.08.010

Fang, X., Wang, Y., Wang, Z., Jiang, Z., and Dong, M., Microorganism assisted synthesized nanoparticles for catalytic applications, *Energies*, *12*(1), 190 (2019). https://doi.org/10.3390/en12010190

Fouda, A., Saad, E., Salem, S., and Shaheen, T., In-Vitro cytotoxicity, antibacterial, and UV protection properties of the biosynthesized Zinc oxide nanoparticles for medical textile applications, *Microb. Pathogen.*, *125*, 252–261 (2018). https://doi.org/10.1016/j.micpath.2018.09.030

Fuwad, A., Ryu, H., Malmstadt, N., Kim, S., and Jeon, T., Biomimetic membranes as potential tools for water purification: Preceding and future avenues. *Desalination*, *458*, 97–115 (2019). https://doi.org/10.1016/j.desal.2019.02.003

Gautam, M., Kim, J. O., and Yong, C. S., Fabrication of aerosol-based nanoparticles and their applications in biomedical fields, *J. Pharm. Invest.*, *51*(4), 361–375 (2021). https://doi.org/10.1007/S40005-021-00523-1

Gautam, P., Singh, A., Misra, K., Sahoo, A., and Samanta, S., Synthesis and applications of biogenic nanomaterials in drinking and wastewater treatment, *Australas. J. Environ. Manage.*, *231*, 734–748 (2019). https://doi.org/10.1016/j.jenvman.2018.10.104

Gopalakrishnan, I., Sugaraj Samuel, R., & Sridharan, K., Nanomaterials-Based Adsorbents for Water and Wastewater Treatments, *Emerging Trends of Nanotechnology in Environment and Sustainability: A Review-Based Approach*, 89–98 (2018). https://doi.org/10.1007/978-3-319-71327-4_11

Govarthanan, M., Jeon, C., Jeon, Y., Kwon, J., Bae, H., and Kim, W., Non-toxic nano approach for wastewater treatment using Chlorella vulgaris exopolysaccharides immobilized in iron-magnetic nanoparticles, *Int. J. Biol. Macromol.*, *162*, 1241–1249 (2020). https://doi.org/10.1016/j.ijbiomac.2020.06.227

Grasso, G., Zane, D., & Dragone, R., Microbial nanotechnology: challenges and prospects for green biocatalytic synthesis of nanoscale materials for sensoristic and biomedical applications. *Nanomaterials*, *10*(1), 11 (2019). https://doi.org/10.3390/nano10010011

Gupta, V., & Nayak, A., Cadmium removal and recovery from aqueous solutions by novel adsorbents prepared from orange peel and Fe2O3 nanoparticles, *Chem. Eng. J.*, *180*, 81–90 (2012). https://doi.org/10.1016/j.cej.2011.11.006

Ha, C., Zhu, N., Shang, R., Shi, C., Cui, J., Sohoo, I., Ihsanullah Sohoo a, Pingxiao Wu and Cao, Y., Biorecovery of palladium as nanoparticles by Enterococcus faecalis and its catalysis for chromate reduction, *Chem. Eng. J*, *288*, 246–254 (2016). https://doi.org/10.1016/j.cej.2015.12.015

Hasan, A., Morshed, M., Memic, A., Hassan, S., Webster, T., and Marei, H., Nanoparticles in tissue engineering: Applications, challenges and prospects, *Int. J. Nanomed.*, *13*, 5637 (2018). https://doi.org/10.2147%2FIJN.S153758

Herlekar, M., Barve, S., and Kumar, R., Plant-mediated green synthesis of iron nanoparticles, *J. Nanopart.*, 2014, 01-09 (2014). http://dx.doi.org/10.1155/2014/140614

Hidangmayum, A., Debnath, A., Guru, A., Singh, B. N., Upadhyay, S. K., and Dwivedi, P., Mechanistic and recent updates in nano-bioremediation for developing green technology to alleviate agricultural contaminants, *Int. J. Environ. Sci. Technol.*, 1–26 (2022). https://doi.org/10.1007/S13762-022-04560-7

Hulikere, M., and Joshi, C., Characterization, antioxidant and antimicrobial activity of silver nanoparticles synthesized using marine endophytic fungus-Cladosporium cladosporioides, *Process Biochem.*, *82*, 199–204 (2019). https://doi.org/10.1016/j.procbio.2019.04.011

Hulkoti, N., and Taranath, T., Biosynthesis of nanoparticles using microbes—a review, *Colloids Surf.*, *B*, *121*, 474–483 (2014). https://doi.org/10.1016/j.colsurfb.2014.05.027

Hussain, T., Akhter, N., Nadeem, R., Rashid, U., Noreen, S., Anjum, S., Ullah, S., Hussain, H. R., Ashfaq, A., Perveen, S., A. Alharthi, F., and Kazerooni, E. A., Biogenic synthesis of date stones biochar-based zirconium oxide nanocomposite for the removal of hexavalent chromium from aqueous solution, *Appl. Nanosci. (Switzerland)*, 1–14 (2022). https://doi.org/10.1007/S13204-022-02599-Z

Ingale, A., and Chaudhari, A., Biogenic synthesis of nanoparticles and potential applications: an eco-friendly approach, *J. Nanomed Nanotechol.*, *4*(2), 1–7 (2013). http://dx.doi.org/10.4172/2157-7439.1000165

Inyinbor Adejumoke, A., Adebesin Babatunde, O., Oluyori Abimbola, P., Adelani Akande Tabitha, A., Dada Adewumi, O., and Oreofe Toyin, A., Water pollution: effects, prevention, and climatic impact, *Water Challenges of an Urbanizing World, 33, 33-47* (2018).

Jain, K., The role of nanobiotechnology in drug discovery, *Drug Discovery Today*, *10*(21), 1435–1442 (2005). https://doi.org/10.1016/S1359-6446(05)03573-7

Jain, K., Patel, A. S., Pardhi, V. P., Jeet, S., Flora, S., Capela, I., and Kamali, M., Nanotechnology in wastewater management: a new paradigm towards wastewater treatment, *Mol.*, *26*(6), 1-26 (2021). https://doi.org/10.3390/molecules26061797

Jena, J., Pradhan, N., Dash, B., Sukla, L., and Panda, P., Biosynthesis and characterization of silver nanoparticles using microalga Chlorococcum humicola and its antibacterial activity, *Int. J. Nanomater Biostruct.*, *3*(1), 1–8 (2013).

Jhaveri, J., and Murthy, Z., A comprehensive review on anti-fouling nanocomposite membranes for pressure driven membrane separation processes, *Desalin.*, *379*, 137–154 (2016). https://doi.org/10.1016/j.desal.2015.11.009

Ji, C., Nguyen, L., Hou, J., Hai, F., and Chen, V., Direct immobilization of laccase on titania nanoparticles from crude enzyme extracts of P. ostreatus culture for micro-pollutant degradation, *Sep. Purif. Technol.*, *178*, 215–223 (2017). https://doi.org/10.1016/j.seppur.2017.01.043

Kapahi, M., and Sachdeva, S., Bioremediation options for heavy metal pollution, *Journal of Health and Pollution*, *9*(24), 1-20 (2019). https://doi.org/10.5696/2156-9614-9.24.191203

Kapoor, R. T., Salvadori, M. R., Rafatullah, M., Siddiqui, M. R., Khan, M. A., and Alshareef, S. A., Exploration of Microbial Factories for Synthesis of Nanoparticles – A Sustainable Approach for Bioremediation of Environmental Contaminants, *Front. Microbiol.*, *12*, 658294 (2021). https://doi.org/10.3389/FMICB.2021.658294/FULL

Khan, F., Shariq, M., Asif, M., Siddiqui, M., Malan, P., and Ahmad, F., Green nanotechnology: plant-mediated nanoparticle synthesis and application, *Nanomater.*, *12*(4), 1-22 (2022). https://doi.org/10.3390/nano12040673

Kinuthia, G., Ngure, V., Beti, D., Lugalia, R., Wangila, A., and Kamau, L., Levels of heavy metals in wastewater and soil samples from open drainage channels in Nairobi, Kenya: community health implication, *Sci. Rep.*, *10*(1), 8434 (2020). https://doi.org/10.1038/s41598-020-65359-5

Koul, B., Poonia, A. K., Yadav, D., and Jin, J. O., Microbe-mediated biosynthesis of nanoparticles: Applications and future prospects, *Biomol.*, *11*(6) , 1-33 (2021). https://doi.org/10.3390/biom11060886

Koul, B., and Taak, P., *Biotechnological strategies for effective remediation of polluted soils*, Springer (2018).

Krstic, V., Urosevic, T., and Pesovski, B., A review on adsorbents for treatment of water and wastewaters containing copper ions, *Chem. Eng. Sci.*, *192*, 273–287 (2018). https://doi.org/10.1016/j.ces.2018.07.022

Kumar, D., Palanichamy, V., and Roopan, S., Green synthesis of silver nanoparticles using Alternanthera dentata leaf extract at room temperature and their antimicrobial activity, *Spectrochim. Acta, Part A*, *127*, 168–171 (2014). https://doi.org/10.1016/j.saa.2014.02.058

Kumar, H., Sinha, S. K., Goud, V. V., & Das, S., Removal of Cr(VI) by magnetic iron oxide nanoparticles synthesized from extracellular polymeric substances of chromium resistant acid-tolerant bacterium Lysinibacillus sphaericus RTA-01, *J. Environ. Health Sci. Eng.*, *17*(2), 1001–1016 (2019). https://doi.org/10.1007/S40201-019-00415-5

Kumar, K., Muralidhara, H., NAyaka, Y., Hanumanthappa, H., Veena, M., and Kumar, S., ZnO-NiO nanocomposites as highly recyclable adsorbent for effective removal of Pb (II) and Cd (II) from aqueous solution. *In International Conference on Advanced Nanomaterials & Emerging Engineering Technologies*, 95–101 (2013). https://doi.org/10.1109/ICANMEET.2013.6609244

Kumar, P., Kumar, A., and Kumar, R., Phytoremediation and Nanoremediation, *New Frontiers of Nanomaterials in Environmental Science*, 281–297 (2021). https://doi.org/10.1007/978-981-15-9239-3_13

Kumar, S., Ahlawat, W., Bhanjana, G., Heydarifard, S., Nazhad, M., and Dilbaghi, N., Nanotechnology-based water treatment strategies, *Journal of Nanoscience and Nanotechnology*, *14*(2), 1838–1858 (2014). https://doi.org/10.1166/jnn.2014.9050

Kumar, V., Kumar, P., Pournara, A., Vellingiri, K., and Kim, K., Nanomaterials for the sensing of narcotics: Challenges and opportunities, *TrAC, Trends Anal. Chem.*, *106*, 84–115 (2018). https://doi.org/10.1016/j.trac.2018.07.003

Kumaresan, M., Anand, K., Govindaraju, K., Tamilselvan, S., and Kumar, V., Seaweed Sargassum wightii mediated preparation of zirconia (ZrO2) nanoparticles and their antibacterial activity against gram positive and gram negative bacteria, *Microb. Pathogen.*, *124*, 311–315 (2018). https://doi.org/10.1016/j.micpath.2018.08.060

Kumari, V., Kaushal, S., and Singh, P., Green synthesis of a CuO/rGO nanocomposite using a Terminalia arjuna bark extract and its catalytic activity for the purification of water, *Mater. Adv.*, *3*(4), 2170–2184 (2022). https://doi.org/10.1039/D1MA00993A

Kumari, V., and Tripathi, A. K., Remediation of heavy metals in pharmaceutical effluent with the help of Bacillus cereus-based green-synthesized silver nanoparticles supported on alumina, *Appl. Nanosci. (Switzerland)*, *10*(6), 1709–1719 (2020). https://doi.org/10.1007/S13204-020-01351-9

Lee, H., Lee, G., Jang, N., Yun, J., Song, J., and Kim, B., Biological synthesis of copper nanoparticles using plant extract, *Nanotechnol.*, *1*(1), 371–374 (2011).

Liu, Y., Jin, X., and Chen, Z., The formation of iron nanoparticles by Eucalyptus leaf extract and used to remove Cr (VI), *Sci. Total Environ.*, *627*, 470–479 (2018). https://doi.org/10.1016/j.scitotenv.2018.01.241

Lunge, S., Singh, S., and Sinha, A., Magnetic iron oxide (Fe3O4) nanoparticles from tea waste for arsenic removal, *J. Magn. Magn. Mater.*, *356*, 21–31 (2014). https://doi.org/10.1016/j.jmmm.2013.12.008

Mahanty, S., Chatterjee, S., Ghosh, S., Tudu, P., Gaine, T., Bakshi, M., Surajit, D., Papita, D., Subarna, B., Sudipta, B. and Chaudhuri, P., Synergistic approach towards the sustainable management of heavy metals in wastewater using mycosynthesized iron oxide nanoparticles: Biofabrication, adsorptive, *J. Water Process Eng.*, *37*, 101426 (2020). https://doi.org/10.1016/j.jwpe.2020.101426

Mittal, A., Chisti, Y., and Banerjee, U., Synthesis of metallic nanoparticles using plant extracts, *Biotechnol. Adv.*, *31*(2), 346–356 (2013). https://doi.org/10.1016/j.biotechadv.2013.01.003

Mohanpuria, P., Rana, N. K., and Yadav, S. K., Biosynthesis of nanoparticles: Technological concepts and future applications, *J. Nanopart. Res.*, *10*(3), 507–517 (2008). https://doi.org/10.1007/S11051-007-9275-X

Mohanraj, R., Gnanamangai, B., Poornima, S., Oviyaa, V., Ramesh, K., Vijayalakshmi, G., and Robinson, J., Decolourisation efficiency of immobilized silica nanoparticles synthesized by actinomycetes, *Materials Today: Proceedings*, *48*, 129–135 (2022). https://doi.org/10.1016/j.matpr.2020.04.139

Moitra, P., Alafeef, M., Alafeef, M., Alafeef, M., Dighe, K., Frieman, M. B., Pan, D., Pan, D., and Pan, D., Selective Naked-Eye Detection of SARS-CoV-2 Mediated by N Gene Targeted Antisense Oligonucleotide Capped Plasmonic Nanoparticles, *ACS Nano*, *14*(6), 7617–7627 (2020). https://doi.org/10.1021/ACSNANO.0C03822

Moulton, M., Braydich-Stolle, L., Nadagouda, M., Kunzelman, S., Hussain, S., and Varma, R., Synthesis, characterization and biocompatibility of “green” synthesized silver nanoparticles using tea polyphenols, *Nanoscale*, *2*(5), 763–770 (2010). https://doi.org/10.1039/C0NR00046A

Mughal, B., Zaidi, S., Zhang, X., and Hassan, S., Biogenic nanoparticles: Synthesis, characterisation and applications, *Applied Sciences*, *11*(6), 2598 (2021). https://doi.org/10.3390/app11062598

Mukherjee, D., Ghosh, S., Majumdar, S., and Annapurna, K., Green synthesis of α-Fe2O3 nanoparticles for arsenic (V) remediation with a novel aspect for sludge management, *J. Environ. Chem. Eng.*, *4*(1), 639–650 (2016). https://doi.org/10.1016/j.jece.2015.12.010

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

Nava, O., Soto-Robles, C., Gomez-Gutierrez, C., Vilchis-Nester, A., Castro-Beltran, A., Olivas, A., and Luque, P., Fruit peel extract mediated green synthesis of zinc oxide nanoparticles, *J. Mol. Struct.*, *1147*, 1–6 (2017). https://doi.org/10.1016/j.molstruc.2017.06.078

Noman, M., Shahid, M., Ahmed, T., Niazi, M., Hussain, S., Song, F., and Manzoor, I., Use of biogenic copper nanoparticles synthesized from a native Escherichia sp. as photocatalysts for azo dye degradation and treatment of textile effluents, *Environ. Pollut.*, *257*, 1-36 (2020). https://doi.org/10.1016/j.envpol.2019.113514

Noor, S., Shah, Z., Javed, A., Ali, A., Hussain, S., Zafar, S., and Muhammad, S., A fungal based synthesis method for copper nanoparticles with the determination of anticancer, antidiabetic and antibacterial activities. *Journal of Microbiological Methods*, *174*, 1-36 (2020). https://doi.org/10.1016/j.mimet.2020.105966

Ohoro, C., Adeniji, A., Okoh, A., and O. O.-I., Distribution and chemical analysis of pharmaceuticals and personal care products (PPCPs) in the environmental systems: A review, *Int. J. Environ. Res. Public Health*, *16(17)*, 1-31 (2019). https://doi.org/10.3390/ijerph16173026

Ovais, M., Khalil, A. T., Islam, N. U., Ahmad, I., Ayaz, M., Saravanan, M., Shinwari, Z. K., and Mukherjee, S., Role of plant phytochemicals and microbial enzymes in biosynthesis of metallic nanoparticles, *Appl. Microbiol. Biotechnol.*, *102*(16), 6799–6814 (2018). https://doi.org/10.1007/S00253-018-9146-7

Oya, N., Keskin, S., Celebioglu, A., Sarioglu, O. F., Uyar, T., and Tekinay, T., Encapsulation of living bacteria in electrospun cyclodextrin ultrathin fibers for bioremediation of heavy metals and reactive dye from wastewater, *Colloids Surf., B.*, *161*, 169–176 (2018). https://doi.org/10.1016/j.colsurfb.2017.10.047

Pandey, N., Shukla, S. K., and Singh, N. B., Water purification by polymer nanocomposites: an overview, *Nanocomposites*, *3*(2), 47–66 (2017). https://doi.org/10.1080/20550324.2017.1329983

Pang, Y., Zeng, G.-M., Tang, L., Zhang, Y., Liu, Y.-Y., Lei, X.-X., Wu, M.-S., Li, Z., and Liu, C., Cr (VI) reduction by Pseudomonas aeruginosa immobilized in a polyvinyl alcohol/sodium alginate matrix containing multi-walled carbon nanotubes, *Bioresour. Technol.*, *102*(22), 10733–10736 (2011). https://doi.org/10.1016/j.biortech.2011.08.078

Park, Y., Hong, Y., Weyers, A., Kim, Y., and Linhardt, R., Polysaccharides and phytochemicals: a natural reservoir for the green synthesis of gold and silver nanoparticles, *IET Nanobiotechnol.*, *5*(3), 69–78 (2011). https://doi.org/10.1049/iet-nbt.2010.0033

Parsons, J., Peralta-Videa, J., and Gardea-Torresdey, J., Use of plants in biotechnology: synthesis of metal nanoparticles by inactivated plant tissues, plant extracts, and living plants, *Developments in Environmental Science*, *5*, 463–485 (2007). https://doi.org/10.1016/S1474-8177(07)05021-8

Patil, S., and Chandrasekaran, R., Biogenic nanoparticles: a comprehensive perspective in synthesis, characterization, application and its challenges, *J. Genet. Eng. Biotechnol.*, 18(1), 67 (2020). https://doi.org/10.1186/s43141-020-00081-3

Pete, A. J., Bharti, B., and Benton, M. G., Nano-enhanced Bioremediation for Oil Spills: A Review, *ACS ES&T Eng.*, *1*(6), 928–946 (2021). https://doi.org/10.1021/ACSESTENGG.0C00217

Poguberovic, S., Krcmar, D., Dalmacija, B., Maletic, S., Tomasevic-Pilipovic, D., Kerkez, D., and Roncevic, S., Removal of Ni (II) and Cu (II) from aqueous solutions using 'green'zero-valent iron nanoparticles produced by oak and mulberry leaf extracts, *Water Sci. Technol.*, *74*(9), 2115–2123 (2016). https://doi.org/10.2166/wst.2016.387

Prakash, A., Sharma, S., Ahmad, N., Ghosh, A., and Sinha, P., Synthesis of AgNps By Bacillus cereus bacteria and their antimicrobial potential, *Journal of Biomaterials and Nanobiotechnology*, *2*(02), 156-162 (2011).

Prasad, K., Jha, A., and Kulkarni, A., Lactobacillus assisted synthesis of titanium nanoparticles. *Nanoscale Research Letters*, *2*(5), 248–250 (2007). https://doi.org/10.1007/s11671-007-9060-x

Qasem, N. A. A., Mohammed, R. H., and Lawal, D. U., Removal of heavy metal ions from wastewater: a comprehensive and critical review, *npj Clean Water*, 4(1), 1-15 (2021). https://doi.org/10.1038/s41545-021-00127-0

Rahman, Z., and Singh, V. P., Bioremediation of toxic heavy metals (THMs) contaminated sites: concepts, applications and challenges, *Environ. Sci. Pollut. Res.*, *27*(22), 27563–27581 (2020). https://doi.org/10.1007/S11356-020-08903-0

Raĭkher, Y. L., Stepanov, V. I., Stolyar, S. V., Ladygina, V. P., Balaev, D. A., Ishchenko, L. A., and Balasoiu, M., Magnetic properties of biomineral particles produced by bacteria Klebsiella oxytoca, *Phys. Solid State*, *52*(2), 298–305 (2010). https://doi.org/10.1134/S1063783410020125

Raj, R., Dalei, K., Chakraborty, J., and Das, S., Extracellular polymeric substances of a marine bacterium mediated synthesis of CdS nanoparticles for removal of cadmium from aqueous solution, *J. Colloid Interface Sci.*, *462*, 166–175 (2016). https://doi.org/10.1016/j.jcis.2015.10.004

Rajeshkumar, S., & Bharath, L., Mechanism of plant-mediated synthesis of silver nanoparticles–a review on biomolecules involved, characterisation and antibacterial activity, *Chem. Biol. Interact.*, *273*, 219–227 (2017). https://doi.org/10.1016/j.cbi.2017.06.019

Rao, A., Bankar, A., Kumar, A., Gosavi, S., and Zinjarde, S., Removal of hexavalent chromium ions by Yarrowia lipolytica cells modified with phyto-inspired Fe0/Fe3O4 nanoparticles, *J. Contam. Hydrol.*, *146*, 63–73 (2013). https://doi.org/10.1016/j.jconhyd.2012.12.008

Rao, C. N. R.,and Biswas, K., Characterization of nanomaterials by physical methods. *Annual Review of Analytical Chemistry*, *2*, 435–462 (2009). https://doi.org/10.1146/ANNUREV-ANCHEM-060908-155236

Rao, K. S., Mohapatra, M., Anand, S., and Venkateswarlu, P., Review on cadmium removal from aqueous solutions, *Sci. Technol.*, *2*(7), 81–103 (2010). https://doi.org/10.4314/ijest.v2i7.63747

Renu, M., Singh, K., Upadhyaya, S., and Dohare, R., Removal of heavy metals from wastewater using modified agricultural adsorbents, *Mater. Today Proc.*, *4*(9), 10534–10538 (2017). https://doi.org/10.1016/j.matpr.2017.06.415

Riddin, T., Gericke, C., and Whiteley, C., Biological synthesis of platinum nanoparticles: effect of initial metal concentration, *Enzyme Microb. Technol.*, *46*(6), 501–505 (2010). https://doi.org/10.1016/j.enzmictec.2010.02.006

Rodovalho, F., Capistrano, G., Gomes, J., Sodre, F., Chaker, J., Campos, A., and Sousa, M., Elaboration of magneto-thermally recyclable nanosorbents for remote removal of toluene in contaminated water using magnetic hyperthermia, *Chem. Eng. J.*, *302*, 725–732 (2016). https://doi.org/10.1016/j.cej.2016.05.110

Roy, A., Elzaki, A., Tirth, V., Kajoak, S., Osman, H., Algahtani, A., and Bilal, M., Biological synthesis of nanocatalysts and their applications. *Catalysts*, *11*(12), 1-22 (2021). https://doi.org/10.3390/catal11121494

Saif, S., Tahir, A., and Chen, Y., Green synthesis of iron nanoparticles and their environmental applications and implications, *Nanomater.*, *6*(11), 1-26 (2016). https://doi.org/10.3390/nano6110209

Saleem, S., Rizvi, A., and Khan, M. S., Microbiome-mediated nano-bioremediation of heavy metals: a prospective approach of soil metal detoxification, *Int. J. Environ. Sci. Technol.*, 1–24 (2022). https://doi.org/10.1007/S13762-022-04684-W

Saleh, T., Parthasarathy, P., and Irfan, M., Advanced functional polymer nanocomposites and their use in water ultra-purification, *Trends Environ. Anal. Chem.*, *24*, 1-11 (2019). https://doi.org/10.1016/j.teac.2019.e00067

Sarioglu, O., Keskin, N. S., Celebioglu, A., Tekinay, T., and Uyar, T., Bacteria immobilized electrospun polycaprolactone and polylactic acid fibrous webs for remediation of textile dyes in water, *Colloids Surf., B.*, *152*, 245–251 (2017). https://doi.org/10.1016/j.colsurfb.2017.01.034

Sathiyanarayanan, G., Dineshkumar, K., and Yang, Y. H., Microbial exopolysaccharide-mediated synthesis and stabilization of metal nanoparticles, *Crit. Rev. Microbiol.*, *43*(6), 731–752 (2017). https://doi.org/10.1080/1040841X.2017.1306689

Sathiyanarayanan, G., Kiran, G., and Selvin, J., Synthesis of silver nanoparticles by polysaccharide bioflocculant produced from marine Bacillus subtilis MSBN17, *Colloids Surf., B.*, *102*, 13–20 (2013). https://doi.org/10.1016/j.colsurfb.2012.07.032

Savage, N., and Diallo, M. S., Nanomaterials and water purification: Opportunities and challenges, *J. Nanopart. Res.*, *7*(4–5), 331–342 (2005). https://doi.org/10.1007/S11051-005-7523-5

Say, R., Yilmaz, N., and Denizli, A., Removal of heavy metal ions using the fungus penicillium canescens, *Adsorpt. Sci. Technol.*, *21*(7), 643–650 (2003). https://doi.org/10.1260/026361703772776420

Seshadri, S., Saranya, K., and Kowshik, M., Green synthesis of lead sulfide nanoparticles by the lead resistant marine yeast, Rhodosporidium diobovatum, *Biotechnol. Progr.*, *27*(5), 1464–1469 (2011). https://doi.org/10.1002/BTPR.651

Shahverdi, A., Minaeian, S., Shahverdi, H., Jamalifar, H., and Nohi, A., Rapid synthesis of silver nanoparticles using culture supernatants of Enterobacteria: a novel biological approach, *Process Biochem.*, *42*(5), 919–923 (2007). https://doi.org/10.1016/j.procbio.2007.02.005

Shankar, P., Shobana, S., Karuppusamy, I., Pugazhendhi, A., Ramkumar, V., Arvindnarayan, S., and Kumar, G., A review on the biosynthesis of metallic nanoparticles (gold and silver) using bio-components of microalgae: Formation mechanism and applications, *Enzyme Microb. Technol.*, *95*, 28–44 (2016). https://doi.org/10.1016/j.enzmictec.2016.10.015

Sharma, A., Sharma, S., Sharma, K., Chetri, S. P. K., Vashishtha, A., Singh, P., Kumar, R., Rathi, B., and Agrawal, V., Algae as crucial organisms in advancing nanotechnology: a systematic review, *J. Appl. Phycol.*, *28*(3), 1759–1774 (2016). https://doi.org/10.1007/S10811-015-0715-1

Sharma, U., and Sharma, J. G., Nanotechnology for the bioremediation of heavy metals and metalloids, *Journal of Applied Biology and Biotechnology*, *10*(5), 34–43 (2022). https://doi.org/10.7324/JABB.2022.100504

Shen, L., Wang, J., Li, Z., Fan, L., Chen, R., Wu, X., Li, J., and Zeng, W., A high-efficiency Fe2O3@ Microalgae composite for heavy metal removal from aqueous solution, *J. Water Process Eng.*, *33*, (2020). https://doi.org/10.1016/j.jwpe.2019.101026

Shin, J., Lee, K., Yeo, T., and Choi, W., Facile One-pot Transformation of Iron Oxides from Fe2O3 Nanoparticles to Nanostructured Fe3O4@C Core-Shell Composites via Combustion Waves, *Sci. Rep.*, *6*(1), 1-10 (2016). https://doi.org/10.1038/srep21792

Shukla, P., Microbial Nanotechnology for Bioremediation of Industrial Wastewater, *Frontiers in Microbiology*, *11*, 1-8 (2020). https://doi.org/10.3389/FMICB.2020.590631/FULL

Simeonov, L., Kochubovski, M., and Simeonova, B., Environmental heavy metal pollution and effects on child mental development: Risk assessment and prevention strategies, *Springer* (2010).

Singh, J., Vishwakarma, K., Ramawat, N., Rai, P., Singh, V. K., Mishra, R. K., Kumar, V., Tripathi, D. K., and Sharma, S., Nanomaterials and microbes' interactions: a contemporary overview, *3 Biotech.*, *9*(3), 1–14 (2019). https://doi.org/10.1007/S13205-019-1576-0

Składanowski, M., Wypij, M., Laskowski, D., Golińska, P., Dahm, H., and Rai, M., Silver and gold nanoparticles synthesized from Streptomyces sp. isolated from acid forest soil with special reference to its antibacterial activity against pathogens, *J. Cluster Sci.*, *28*(1), 59–79 (2017). https://doi.org/10.1007/S10876-016-1043-6

Soppe, A., Heijman, S., Gensburger, I., Shantz, A., Van Halem, D., Kroesbergen, J., and Smeets, P., Critical parameters in the production of ceramic pot filters for household water treatment in developing countries, *J. Water Health*, *13*(2), 587–599 (2015). https://doi.org/10.2166/wh.2014.090

Southam, G., and Beveridge, T., The in vitro formation of placer gold by bacteria, *Geochim. Cosmochim. Acta*, *58*(20), 4527–4530 (1994). https://doi.org/10.1016/0016-7037(94)90355-7

Srivastava, S. K., and Constanti, M., Room temperature biogenic synthesis of multiple nanoparticles (Ag, Pd, Fe, Rh, Ni, Ru, Pt, Co, and Li) by Pseudomonas aeruginosa SM1, *J. Nanopart. Res.* , *14*(4), 1–10 (2012). https://doi.org/10.1007/S11051-012-0831-7

Srivastava, S., Yamada, R., Ogino, C., and Kondo, A., Biogenic synthesis and characterization of gold nanoparticles by Escherichia coli K12 and its heterogeneous catalysis in degradation of 4-nitrophenol, *Nanoscale Res. Lett.*, *8*(1), 1–9 (2013). https://doi.org/10.1186/1556-276X-8-70

Subbaiya, R., Saravanan, M., Priya, A. R., Shankar, K. R., Selvam, M., Ovais, M., Balajee, R., & Barabadi, H., Biomimetic synthesis of silver nanoparticles from Streptomyces atrovirens and their potential anticancer activity against human breast cancer cells, *IET Nanobiotechnol.*, *11*(8), 965–972 (2017). https://doi.org/10.1049/IET-NBT.2016.0222

Subramaniyam, V., Subashchandrabose, S. R., Thavamani, P., Megharaj, M., Chen, Z., and Naidu, R., Chlorococcum sp. MM11—a novel phyco-nanofactory for the synthesis of iron nanoparticles, *J. Appl. Phycol.*, *27*(5), 1861–1869 (2015). https://doi.org/10.1007/S10811-014-0492-2

Sudhakar, M., Aggarwal, A., and Sah, M., Engineering biomaterials for the bioremediation: Advances in nanotechnological approaches for heavy metals removal from natural resources, *In Emerging Technologies in Environmental Bioremediation*,2020, 323–339 (2020). https://doi.org/10.1016/B978-0-12-819860-5.00014-6

Thilakan, D., Patankar, J., Khadtare, S., Wagh, N., Lakkakula, J., El-Hady, K., and Tarique, M., Plant-Derived Iron Nanoparticles for Removal of Heavy Metals, *Int. J. Chem. Eng.*, 2022, 1-12 (2022). https://doi.org/10.1155/2022/1517849

Torimiro, N., Daramola, O., Oshibanjo, O., Otuyelu, F., Akinsanola, B., Yusuf, O., and Omole, R., Ecorestoration of heavy metals and toxic chemicals in polluted environment using microbe-mediated nanomaterials, *International Journal of Environmental Bioremediation & Biodegradation*, *9(1)*, 8–21 (2021). https://doi.org/10.12691/ijebb-9-1-2

Tosco, T., Papini, M., Viggi, C., and Sethi, R., Nanoscale zero-valent iron particles for groundwater remediation: a review, *J. Cleaner Prod.*, *77*, 10–21 (2014). https://doi.org/10.1016/j.jclepro.2013.12.026

Tratnyek, P., and Johnson, R., Nanotechnologies for environmental cleanup, *Nano Today*, *1*(2), 44–48 (2006). https://doi.org/10.1016/S1748-0132(06)70048-2

Tripathi, S., Sanjeevi, R., Anuradha, J., Chauhan, D., and Rathoure, A., Nano-bioremediation: nanotechnology and bioremediation, *In Research Anthology On Emerging Techniques in Environmental Remediation*, 135–149 (2022). https://doi.org/10.4018/978-1-6684-3714-8.ch007

Tsekhmistrenko, S., Bityutskyy, V., Tsekhmistrenko, O., Horalskyi, L., Tymoshok, N., and Spivak, M., Bacterial synthesis of nanoparticles: A green approach, *Biosystems Diversity*, *28*(1), 9–17 (2020). https://doi.org/10.15421/012002

Uzair, B., Liaqat, A., Iqbal, H., Menaa, B., Razzaq, A., Thiripuranathar, G., and Meena, F., Green and cost-effective synthesis of metallic nanoparticles by algae: Safe methods for translational medicine, *Bioengineering*, *7*(4), 129 (2020). https://doi.org/10.3390/bioengineering7040129

Verma, A., Dua, R., Singh, A., and Bishnoi, N., Biogenic sulfides for sequestration of Cr (VI), COD and sulfate from synthetic wastewater, *Water Sci.*, *29*(1), 19–25 (2015). https://doi.org/10.1016/j.wsj.2015.03.001

Wang, L., Chen, X., Wang, H., Zhang, Y., Tang, Q., and Li, J., Chlorella vulgaris cultivation in sludge extracts from 2, 4, 6-TCP wastewater treatment for toxicity removal and utilization, *J. Environ. Manage.*, *187*, 146–153 (2017). https://doi.org/10.1016/j.jenvman.2016.11.020

Wang, Y., Zhang, Y., Hou, C., and Liu, M., Mussel-inspired synthesis of magnetic polydopamine–chitosan nanoparticles as biosorbent for dyes and metals removal, *J. Taiwan Inst. Chem. Eng.*, *61*, 292–298 (2016). https://doi.org/10.1016/j.jtice.2016.01.008

Manar, E. A., Nermine, E. M., Reem, K. F. and Abdul-Raheim M. A. R., Wastewater treatment methodologies, review article, *Int. J. Environ & Agri Sci., 3(1), 1-25 (*2023).

Wen, L., Lin, Z., Gu, P., Zhou, J., Yao, B., Chen, G., and Fu, J., Extracellular biosynthesis of monodispersed gold nanoparticles by a SAM capping route, *J. Nanopart. Res.*, *11*(2), 279–288 (2008). https://doi.org/10.1007/s11051-008-9378-z

Wright, M. H., Farooqui, S. M., White, A. R., and Greene, A. C., Production of manganese oxide nanoparticles by Shewanella species, *Appl. Environ. Microbiol.*, *82*(17), 5402–5409 (2016). https://doi.org/10.1128/AEM.00663-16

Yadav, A., Kon, K., Kratosova, G., Duran, N., Ingle, A. P., and Rai, M., Fungi as an efficient mycosystem for the synthesis of metal nanoparticles: Progress and key aspects of research, *Biotechnol. Lett.*, *37*(11), 2099–2120 (2015). https://doi.org/10.1007/s10529-015-1901-6

Yadav, D., and Srivastava, S., Carbon nanotubes as adsorbent to remove heavy metal ion (Mn+ 7) in wastewater treatment, *Mater. Today Proc.*, *4*(2), 4089–4094 (2017). https://doi.org/10.1016/j.matpr.2017.02.312

Yadav, V., Gadi, R., and Kalra, S., Clay based nanocomposites for removal of heavy metals from water: A review, *J. Environ. Manage.*, *232*, 803–817 (2019). https://doi.org/10.1016/j.jenvman.2018.11.120

Yamakata, A., and Vequizo, J., Curious behaviors of photogenerated electrons and holes at the defects on anatase, rutile, and brookite TiO2 powders: A review, *J. Photochem. Photobiol.*, *C*, *40*, 234–243 (2019). https://doi.org/10.1016/j.jphotochemrev.2018.12.001

Yan, F., Wu, C., Cheng, Y., He, Y., Li, W., and Yu, H., Carbon nanotubes promote Cr (VI) reduction by alginate-immobilized Shewanella oneidensis MR-1, *Biochem. Eng. J.*, *77*, 183–189 (2013). https://doi.org/10.1016/j.bej.2013.06.009

Yang, X., Zhao, Z., Yu, Y., Shimizu, K., Zhang, Z., Lei, Z., and Lee, D., Enhanced biosorption of Cr (VI) from synthetic wastewater using algal-bacterial aerobic granular sludge: Batch experiments, kinetics and mechanisms, *Sep. Purif. Technol.*, *251*, 1-7 (2020). https://doi.org/10.1016/j.seppur.2020.117323

Yaqoob, A. A., Parveen, T., Umar, K., Nasir, M., and Ibrahim, M., Role of nanomaterials in the treatment of waste water: A review, *Water*, *12*(2), 1-30 (2020). https://doi.org/10.3390/w12020495

Yu, L., Ruan, S., Xu, X., Zou, R., and Hu, J., One-dimensional nanomaterial-assembled macroscopic membranes for water treatment, *Nano Today*, *17*, 79–95 (2017). https://doi.org/10.1016/j.seppur.2020.117323

Zhang, G., Liu, Z., Xiao, Z., Huang, J., Li, Q., Wang, Y., and Sun, D., Ni2P-graphite nanoplatelets supported Au-Pd core-shell nanoparticles with superior electrochemical properties, *J. Phys. Chem. C.*, *119*(19), 10469–10477 (2015). https://doi.org/10.1021/ACS.JPCC.5B02107

Zhang, X., Yan, S., Tyagi, R., and Surampalli, R., Synthesis of nanoparticles by microorganisms and their application in enhancing microbiological reaction rates, *Chemosphere*, *82*(4), 489–494 (2011). https://doi.org/10.1016/j.chemosphere.2010.10.023

Zhao, X., Lv, L., Pan, B., Zhang, W., Zhang, S., and Zhang, Q., Polymer-supported nanocomposites for environmental application: A review, *Chem. Eng. J.*, *170*(2–3), 381–394 (2011). https://doi.org/10.1016/j.cej.2011.02.071

Zhou, D., Kim, D., and Ko, S., Heavy metal adsorption with biogenic manganese oxides generated by Pseudomonas putida strain MnB1, *J. Ind. Eng. Chem.*, *24*, 132–139 (2015). https://doi.org/10.1016/j.jiec.2014.09.020