

Review

Biological Synthesis of Nanocatalysts and Their Applications

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Abstract: Over the past few decades, the synthesis and potential applications of nanocatalysts have received great attention from the scientific community. Many well-established methods are extensively utilized for the synthesis of nanocatalysts. However, most conventional physical and chemical methods have some drawbacks, such as the toxicity of precursor materials, the requirement of high-temperature environments, and the high cost of synthesis, which ultimately hinder their fruitful applications in various fields. Bioinspired synthesis is eco-friendly, cost-effective, and requires a low energy/temperature ambient. Various microorganisms such as bacteria, fungi, and algae are used as nano-factories and can provide a novel method for the synthesis of different types of nanocatalysts. The synthesized nanocatalysts can be further utilized in various applications such as the removal of heavy metals, treatment of industrial effluents, fabrication of materials with unique properties, biomedical, and biosensors. This review focuses on the biogenic synthesis of nanocatalysts from various green sources that have been adopted in the past two decades, and their potential applications in different areas. This review is expected to provide a valuable guideline for the biogenic synthesis of nanocatalysts and their concomitant applications in various fields.

Keywords: green source; nanocatalysts; nanoparticles; bacteria; fungi; algae; applications

1. Introduction

Nanotechnology has evolved as a highly technical research arena with potential applications in all spheres of life. The term “nano” has been derived from the Greek for “dwarf.” With a clear idea of the extremity of something in a nano, a nanoparticle can be defined as particles that have at least one dimension below 100 nm [1]. Several bulk materials show completely different properties when they are studied on the nanoscale. One known reason for this phenomenon is their higher surface-to-volume aspect ratio.

For different nanoparticles, this can result in a variety of characteristics. For example, the higher aspect ratio of silver nanoparticles allows them to have increased efficacy in antibacterial properties. Consequently, silver nanoparticles can have diverse applications in cosmetics, packaging, electronics, coatings, and biotechnology [2,3]. A unique property of nanoparticles is that they have the ability to combine or form a solid at lower temperatures without melting. This property helps to achieve improved coatings on capacitors and other electronic components. Nanoparticles are also transparent, which allows them to be utilized in packaging, coating, and cosmetics (e.g., scratchproof eyeglasses, crack-resistant paints). When metallic nanoparticles are attached to single-stranded DNA, they can travel through the bloodstream and confine any target organ. This characteristic can be exploited in medical diagnostics, therapeutics, and other biomedical applications. Due to their significant potentials, nanoparticles must be further studied to find unexplored uses in everyday life [4].

Nanocatalysts are usually differentiated based on their dimension, composition, morphology, material nature, agglomeration, and uniformity. The morphology and shape of nanoparticles have vital functions, such as their toxic effect on mankind or the environment [5]. On the basis of dimension, nanoparticles can be one-dimensional, two-dimensional, and three-dimensional. Thin-film coatings used in sensors and electronic devices come under 1D, whereas carbon nanotubes, wires, fibers, etc. belong to 2D nanoparticles. Three dimensional nanoparticles include quantum dots, hollow spheres, and dendrimers. On the basis of morphology, they can be spherical, flat, crystalline, cubic, etc. structures and present in either single or composite form.

Numerous physical and chemical approaches can be effectively utilized for nanocatalyst synthesis. These include aerosol technologies, microemulsion, microwave, laser ablation, lithography, photochemical reduction, ion sputtering, sol-gel, sonochemical, ultrasonic spark discharge, and template synthesis [6]. However, most approaches have some nonnegligible drawbacks as these processes use expensive and hazardous chemicals and consume a lot of energy. Chemical synthesis has proved to be useful and can be used for a long time, but they have certain demerits such as the aggregation of particles when allowed to react for a long time, instability of the final product, and improper control of crystal growth [7]. Moreover, this method is not environmentally friendly, as a lot of toxic wastes and pollutants are generated as by-products. In particular, both physical and chemical techniques produce harmful pollutants such as harmful capping and reducing agents and organic solvents. Therefore, the use of harmful chemicals and organic solvents involved in nanomaterial synthesis should be reduced [8]. Hence, both conventional methods of nanoparticle synthesis, i.e., physical and chemical methods, have evolved as costly and are not friendly to the ecosystem. The demerits of these methods lead to the development of novel methods for the synthesis of nanomaterials that should be environmentally friendly, cheap, nonhazardous, clean, and energy-efficient [9]. Recently, the focus has shifted to the utilization of biological agents for the synthesis of nanomaterials due to their various advantages as compared to chemical and physical ones. Biological methods of synthesis are generally utilized by biological entities such as algae, fungi, and bacteria [10].

There are different groups of nanoparticles available, which include carbon-based nanoparticles, ceramic nanoparticles, semiconductor nanoparticles, metal/metal oxide nanoparticles, and polymeric nanoparticles [11–17]. Metal/metal oxide nanoparticles have gained significant interest due to their wide range of applications such as the detection and imaging of biomolecules, antimicrobial activity, removal of environmental pollutants, and bioanalytical applications [11]. These nanoparticles are prepared from the metal/metal oxide precursors. Metal/metal oxide nanoparticles include silver, copper, gold, titanium oxide, iron oxide, and zinc oxide [11]. They can be synthesized by chemical, physical, electrochemical, or photochemical approaches. However, due to their negative impact, biological methods have been currently in demand. Therefore, in this review, an overview of different methods of synthesis, and the use of various biological agents such as algae, fungi,

and bacteria, which are used for the synthesis of metal/metal oxide nanocatalysts, is discussed. Further discussion of the application of nanocatalysts in different sectors is conducted.

2. Different Methods of Nanocatalyst Synthesis

Generally, there are two techniques for nanocatalyst synthesis: top-down and bottom-up. In the first method, the bulk material is broken down into smaller nanosized particles [18,19]. Various metallic nanoparticles are composed of top-down methods such as etching, sputtering, and laser ablation. On the other hand, the bottom-up method involves joining a molecule by a molecule, atom by atom, and clusters by cluster. In this method, single molecules are explored to form a complex structure of nanoscale size [20]. Various methods that use bottom-up techniques include supercritical fluid synthesis, plasma or flame spraying synthesis, laser pyrolysis, molecular condensation, the sol-gel process, chemical reduction, and green synthesis (Figure 1). In this technique, physicochemical reactions occur that may affect the properties of nanoparticles, and the nanoparticles are collected from smaller units. Therefore, both techniques are controlled by kinetic processes, which regulate the size and shapes of the synthesized nanoparticles.

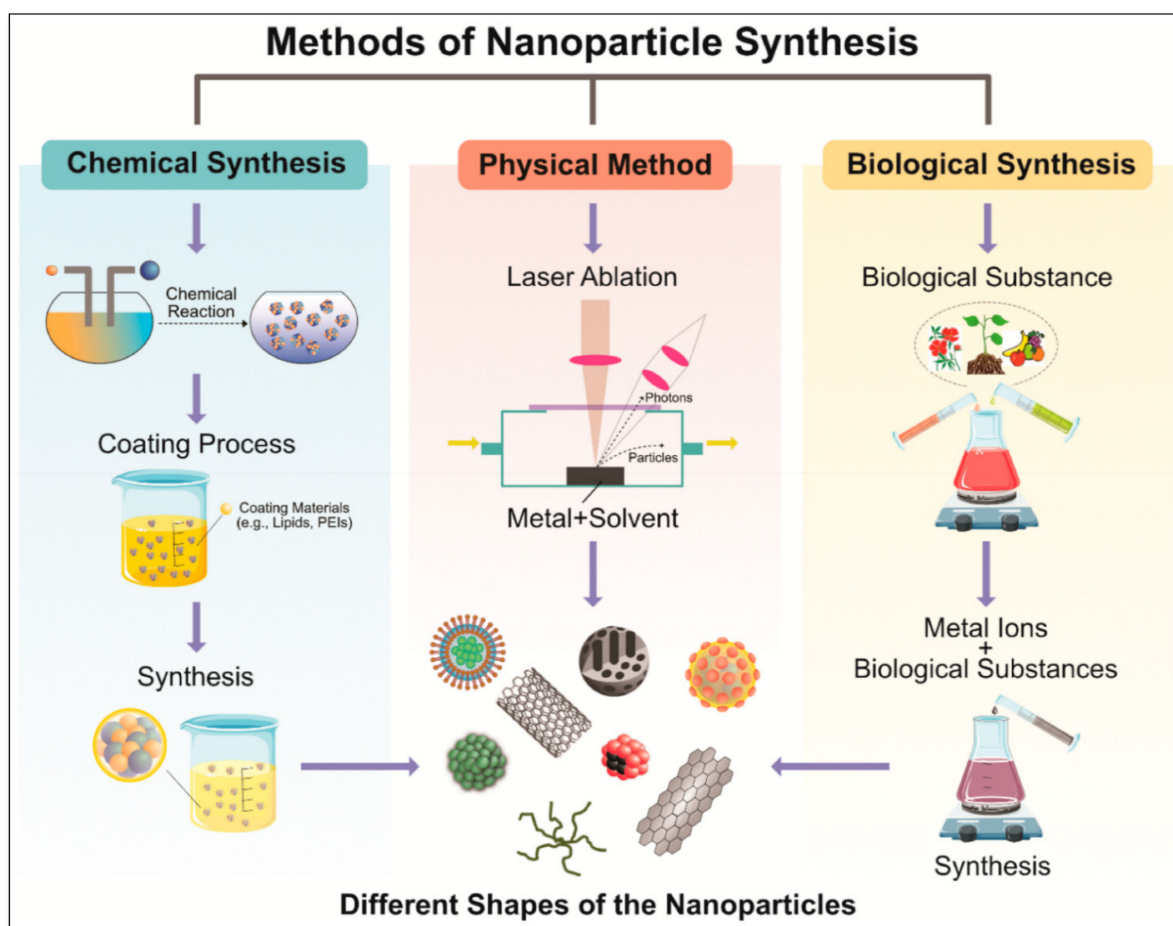


Figure 1. Method of nanoparticles synthesis [21].

3. Biological Approach for Nanocatalyst/Nanoparticle Synthesis

The biological method is preferred over the other two conventional methods (top-down and bottom-up) as it is a green method, environmentally friendly, and does not require a higher energy consumption [22]. Nanoparticles obtained through the biological approach have a greater specific surface area, increase the rate of catalysis, and have metal salt and improved enzymes [23]. Hence, the main objective in the synthesis of nanoparticles using a biological approach is to utilize cheap resources and facilitate a

continuous production of nanoparticles. Biological sources that are used for nanoparticle synthesis provide a simple method and easy increase in biomass, ensuring a uniform particle size, as well as multiplication. The use of microbes is one of the most prominent methods among the biological approaches of nanoparticle synthesis. It utilizes different biological sources such as bacteria, fungi, and algae (Figure 2). Bacteria are the most commonly found organism in our biosphere. Under optimal conditions such as pH, temperature, and pressure, bacteria show the capability to synthesize various nanoparticles [24] (Figure 3). The ability of bacterial cells to survive and proliferate under extreme climatic conditions make them the most ideal organisms for nanoparticle synthesis. They can reproduce and multiply even under high metal concentrations, which may be due to particular resistance mechanisms.

Strains of bacteria that are not resistant to high metal concentrations can also be employed as appropriate microbes. The nanoparticles produced by microorganisms have important uses in the biological field such as bioleaching, biocorrosion, biomineralization, and bioremediation. In addition to bacteria, fungi and algae are two other green sources that are capable of synthesizing nanoparticles. Fungi have an outstanding ability for the synthesis of various bioactive compounds that have potential for numerous applications. They are widely used as reducing and stabilizing agents and can be easily grown on a large scale for the production of nanoparticles with controlled shape and size [25]. Similarly, algae have the ability to synthesize various bioactive compounds, pigments, and proteins, which help in the reduction of salts and act as capping agents in the synthesis mechanism [26].

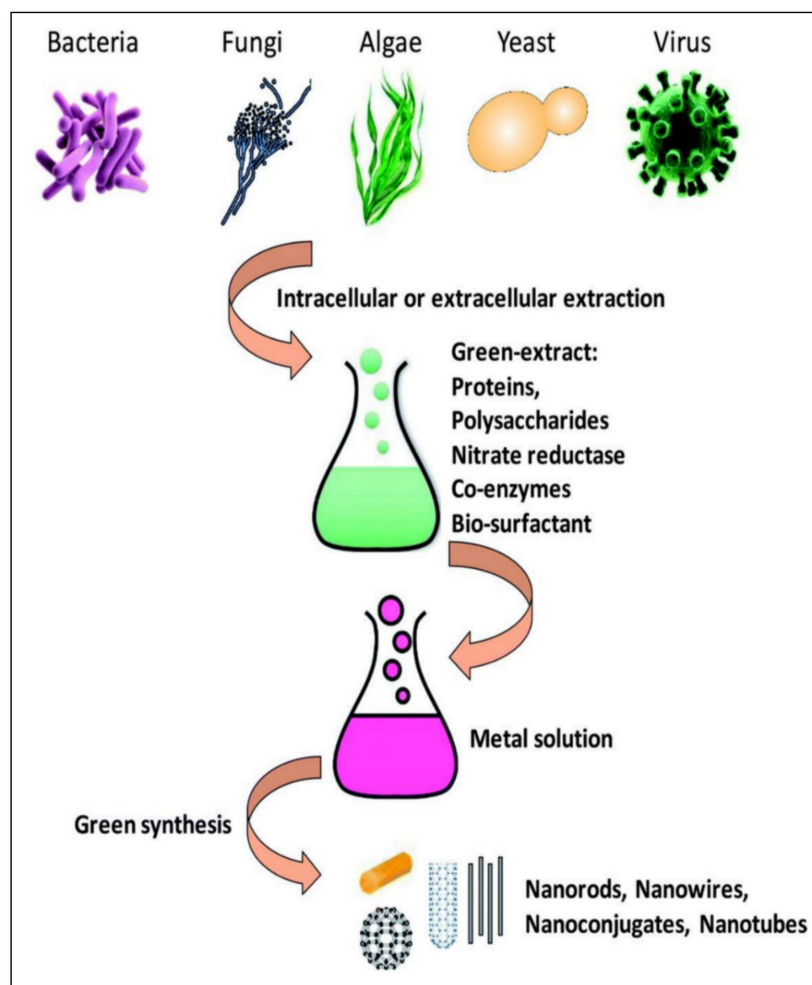


Figure 2. Biological approach to nanoparticle synthesis [26].

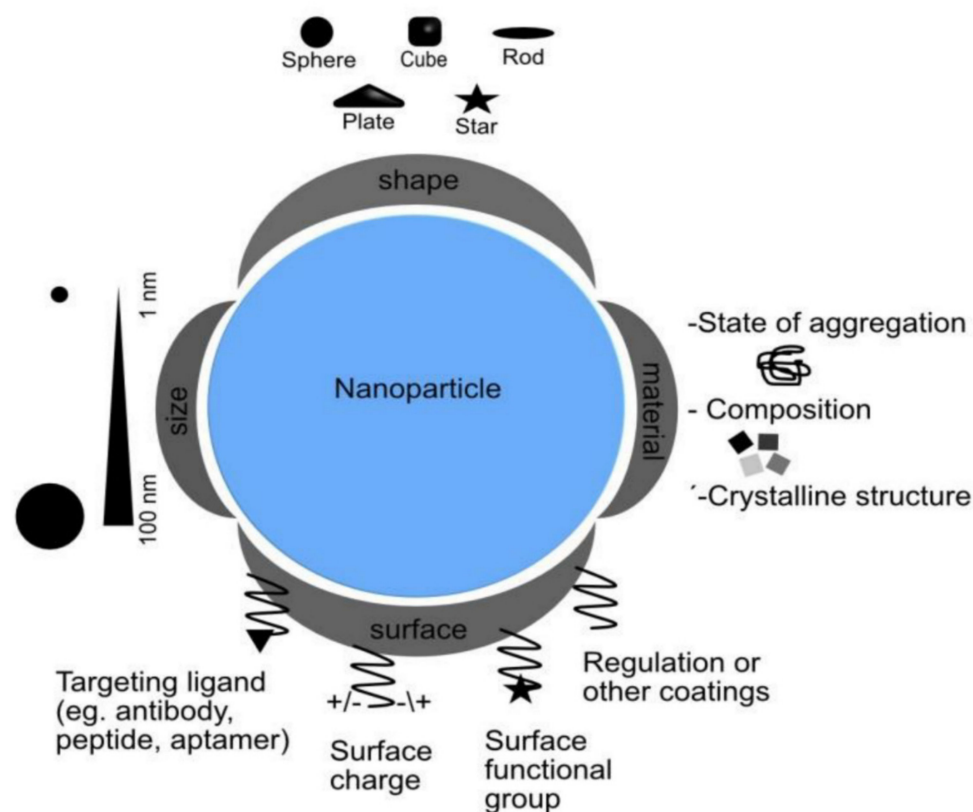


Figure 3. Different physicochemical properties of nanoparticles [24].

3.1. Bacterial Synthesis

In the vast field of biological resources, prokaryotic bacteria are the most researched for the synthesis of metallic nanoparticles. This is because they are relatively easy to manipulate compared to any other living organisms. Various researchers have shown the bacterial synthesis of nanoparticles that were responsible for the reduction of metal ions. The main benefit of bacterial synthesis is their higher reproduction with negligible uses of toxic chemicals. Nevertheless, there are some problems associated with the bacterial synthesis of nanoparticles such as the time-consuming culturing process, and difficulties in controlling the shape, size, and distribution. A study conducted with *Lactobacillus* strains that were extracted from common buttermilk showed a highly concentrated metallic ion. This process produced multiple, highly structured gold and silver nanoparticles. *Lactobacillus* was observed to synthesize nanoparticles within the plasma membrane and remained viable [27]. Ahmad et al. [28] reported the synthesis of gold nanoparticles using *Thermomonospora* sp.—an extremophilic actinomycetes strain and with another novel alkalotolerant actinomycete, i.e., *Rhodococcus* species. Another study reported the influence of the microbial synthesis of gold nanoparticles by changing the pH conditions of *Shewanella algae*. It was found that at pH 7, the nanoparticles synthesized ranged from 10 to 20 nm; however, when the pH was adjusted to 1, the size was modified to 50–500 nm [29]. In a study, *Rhodopseudomonas casulata* was used for the synthesis of gold nanoparticle synthesis. It was found that at pH 7, spherical-shaped nanoparticles were synthesized, but as the pH dropped to 4, the nanoparticles produced were plate-shaped [30]. Parikh et al. [31] reported the synthesis of silver nanoparticles using a bacterial strain, i.e., *Morganella* sp., which was isolated from an insect midgut. When exposed to silver nitrate, *Morganella* sp. synthesized crystalline silver nanoparticles extracellularly. Reddy et al. [32] reported the synthesis of silver and gold nanoparticles using *Bacillus subtilis*. They observed that silver nanoparticles were entirely synthesized extracellularly and formed after 7 days of the addition of silver ions, whereas gold nanoparticles were synthesized both extracellularly and intracellularly and formed after 1 day of addition of salt. Bruna et al. [33] reported the

synthesis of CdS fluorescent nanoparticles using *Halobacillus* sp. They observed that the synthesized nanoparticles were hexagonal at 2–5 nm in size. Further details of nanoparticles synthesized using bacterial cultures are presented in Table 1.

Table 1. Nanoparticles synthesized from bacteria.

Source	Metal	Size (nm)	Shape	Location	References
<i>Actinobacter</i> spp.	M	10–40 (24 h) 50–150 (48 h)	Quasi-spherical cubic	E	[34]
<i>Verticillium luteoalbum</i>	G	100	Spherical, Triangular, Hexagonal	I and E	[35]
<i>Bacillus selenitireducens</i>	T	~10	Nanorods	E	[36]
<i>Escherichia coli</i> DH5a	G	25 ± 8	Spherical	I	[37]
<i>Klebsiella pneumoniae</i>	S	5–32	-	E	[38]
<i>Bacillus licheniformis</i>	S	50	-	E	[39]
<i>Stenotrophomonas maltophilia</i>	G	~40	-	I	[40]
<i>Bacillus</i> sp.	S	5–15	-	I	[41]
<i>Bacillus megatherium</i> D01	G	1.9 ± 0.8	Spherical	E	[42]
<i>Shewanella algae</i>	G	9.6	Spherical	E	[43]
<i>Trichoderma viride</i>	S	2–4	Spherical	E	[44]
<i>Streptomyces</i> sp.	S	10–100	Spherical	E	[45]
<i>Bacillus cereus</i>	S	10–30	Spherical	E	[46]
<i>Pseudomonas aeruginosa</i>	S	13	Spherical	E	[47]
<i>Idiomarina</i> sp. PR58-8	S	26	-	I	[48]
<i>Pseudomonas fluorescens</i>	G	50–70	Spherical	E	[49]
<i>Vibrio alginolyticus</i>	S	50–100	Spherical	I and E	[50]
<i>Azospirillum brasilense</i>	G	5–50	Nanospheres	E	[51]
<i>Planomicrobium</i> sp.	TO	8.89	Spherical	E	[52]
<i>Salmonella typhirium</i>	S	50–150	-	E	[53]
<i>Geobacillus</i> sp.	G	5–50	Quasi-hexagonal	I	[54]
<i>Lactobacillus crispatus</i>	T	70.98	-	E	[55]
<i>Bacillus strain</i> CS 11	S	42–94	Spherical	I and E	[56]
<i>Pseudomonas fluorescens</i>	C	49	Spherical, Hexagonal	E	[57]
<i>Stereum hirsutum</i>	C/CO	5–20	Spherical	E	[58]
<i>Salmonella typhimurium</i>	C	40–60	-	E	[59]
<i>Bhargavaea indica</i>	S	30–100	Pentagon, spherical, icosahedron, nanobar, hexagonal, truncated triangle, and triangular	E	[60]
<i>Exiguobacterium mexicanum</i>	S	5–40	-	I and E	[61]
<i>Deinococcus radiodurans</i>	G	43.75	Spherical, triangular, and irregular	I and E	[62]
<i>Sporosarcina koreensis</i>	G and S	-	Spherical	E	[63]
<i>Bacillus brevis</i>	S	41–68	Spherical	E	[64]
<i>Alcaligenes</i> sp.	S	30–50	Spherical	-	[65]
<i>Marinobacter algicola</i>	G	4–168	Spherical, triangular, pentagonal, and hexagonal	I	[66]
<i>Paracoccus haeundaensis</i>	G	20.93 ± 3.46	Spherical	E	[67]
<i>Bacillus</i> sp.	S	5–15	Spherical	-	[68]

S = silver, G = gold, C = copper, CO = copper oxide, T = titanium, TO = titanium oxide, TE = tellurium, M = magnetite, Z = zirconia, ZO = zinc oxide, IO = iron oxide, P = palladium, E = extracellular, I = intracellular.

3.2. Fungal Synthesis

The use of fungi as a biological agent to synthesize metal nanoparticles has become popular because they show some advantages over bacteria. The presence of mycelia that enhances the surface area of fungi, and the economic utility and simplicity of the scaleup and downstream processing of fungi offer significant merits in using fungi as an agent for the synthesis of nanoparticles [69]. Fungi are also able to produce various enzymes, which help in nanoparticles synthesis with different shapes and sizes. As a result of their larger

biomass compared to that of bacteria, the production of nanoparticles is higher. Various fungal species such as *Fusarium oxysporum*, *Aspergillus oryzae*, *Verticillium luteoalbum*, *Alternata alternata*, and *Collitotrichum* sp. were utilized for nanoparticles synthesis. However, some of the drawbacks of using fungi include laborious and more costly downstream processes. Nanoparticle synthesis using fungal culture can be intracellular or extracellular. In intracellular synthesis, the metal precursor is added to the fungal culture and biomass internalization of the precursor. Nanoparticle extraction is performed by breaking cells using different methods such as chemical treatment, centrifugation, and filtration [70]. In the case of extracellular synthesis, aqueous filtrate that contains fungal bioactive compounds are mixed with the metal precursor; hence, the synthesis process occurs easily. Extracellular synthesis is the most commonly used technique [71]. Mukherjee et al. [72] reported the production of gold nanoparticles by *Verticillium* sp. where the intracellular gold nanoparticles were located on the mycelial surface. A study reported the use of *Fusarium oxysporum* for the synthesis of silver nanoparticles where pure silver nanoparticles were produced with size ranges from 5 to 15 nm, and their capping was performed in such a way that they could be stabilized via the fungal proteins [28]. Bhainsa and D'Souza [73] reported the use of *Aspergillus fumigatus* to produce extracellular silver nanoparticles of 5–25 nm in size. Riddin et al., [74] reported the synthesis of platinum nanoparticles by *F. oxysporum*. The intracellular and extracellular synthesis of the nanoparticles was observed, but the extracellular synthesis was more prominent, and the production of extracellular nanoparticles was found to be 5.66 mg/L. Rai et al. [75] used *Fusarium oxysporum* for the synthesis of zinc sulfide, sulfur, molybdenum sulfide, cadmium sulfide, and lead sulfide nanoparticles. Sanghi et al. [76] used *Coriolus versicolor* for the synthesis of intracellular silver nanoparticles. When the reaction conditions were changed, it was observed that both the extracellular and intracellular synthesis of nanoparticles could be performed by the fungus. Vahabi et al. [77] used *Trichoderma reesei* for the synthesis of extracellular silver nanoparticles and found size ranges of 5–50 nm. Castro-Longoria et al. [78] reported the production of platinum nanoparticles by *Neurospora crassa*. Intracellular platinum nanoparticles were in the size range of 4–35 nm and spherical. Arun et al. [79] reported the synthesis of silver nanoparticles using *Schizophyllum commune* and found that the synthesized nanoparticles were spherical with sizes ranging from 54 to 99 nm. Gudikandula et al. [71] used 55 strains of white rot fungi (basidiomycetes) for the synthesis of silver nanoparticles. They found that the synthesized nanoparticles were 15–25 nm in size with a spherical to round shape. Molnár et al. [70] used 29 different thermophilic filamentous fungi for the synthesis of gold nanoparticles, and the mechanism was intracellular where the synthesized nanoparticles were 1–80 nm in size with a hexagonal and spherical shape. A study reported the synthesis of silver nanoparticles using *Botryosphaeria rhodiana*, and it found that the synthesized nanoparticles were spherical with sizes ranging from 2 to 50 nm [80]. More details of the nanoparticles synthesized using fungal cultures are presented in Table 2.

Table 2. Nanoparticles synthesized from fungus.

Source	Metal	Size (nm)	Shape	Location	Reference
<i>Fusarium oxysporum</i>	G	20–40	Spherical; triangular	E	[81]
<i>Phoma</i> sp. 3.2883	S	71.06–74.46	-	E	[82]
<i>Fusarium oxysporum</i>	Z	3–11	Regular	E	[83]
<i>Trichothecium</i> sp.	G	10–25	Hexagonal, triangular	E	[84]
<i>Fusarium oxysporum</i>	M	20–50	Quasi-spherical	E	[85]
<i>Phaenerochaete chrysosporium</i>	S	50–200	Pyramid	E	[86]
<i>Fusarium oxysporum</i>	S	1.6	Spherical	E	[87]
<i>Trichoderma asperellum</i>	S	13–18	-	E	[88]
<i>Fusarium acuminatum</i>	S	5–40	Spherical	E	[89]
<i>Rhizopus oryzae</i>	G	10	Spherical	-	[90]
<i>Aspergillus clavatus</i>	S	10–25	Spherical, hexagonal	E	[91]
<i>Aspergillus clavatus</i>	G	20–35	nanotriangle	I	[92]

Table 2. Cont.

Source	Metal	Size (nm)	Shape	Location	Reference
<i>Rhizopus stolonier</i>	S	5–50	Spherical	E	[93]
<i>Aspergillus terreus</i>	S	1–20	Spherical	E	[94]
<i>Aspergillus fumigatus</i>	ZO	1.2–6.8	Spherical	E	[95]
<i>Macrophomina phaseolina</i>	S	5–40	Spherical	E	[96]
<i>Penicillium chrysogenum</i>	S	19–60	Spherical	E	[97]
<i>Penicillium nalgiovense</i>	S	15.2 ± 2.6	Spherical	E	[98]
<i>Aspergillus flavus</i>	TO	12–15	-	E	[99]
<i>Trichoderma viride</i>	S	1–50	Globular	-	[100]
<i>Phoma exigua</i>	S	22	Spherical	E	[101]
<i>Phenerochaete chrysosporium</i>	S	34–90	Spherical, oval	E	[102]
<i>Beauveria bassiana</i>	S	10–50	Circular, triangular, hexagonal	E	[103]
<i>Cladosporium cladosporioides</i>	S	30–60	Spherical	E	[104]
<i>Phomopsis helianthin</i>	S	5–60	Spherical, hexagonal	E	[105]
<i>Fusarium solani</i>	G	40–45	Needle, flower-like	-	[106]
<i>Aspergillus niger</i>	IO	20–40	Flake	E	[107]

S = silver, G = gold, C = copper, CO = copper oxide, T = titanium, TO = titanium oxide, TE = tellurium, M = magnetite, Z = zirconia, ZO = zinc oxide, IO = iron oxide, P = palladium, E = extracellular, I = intracellular.

3.3. Algal Synthesis

Algae are an economically important group of organisms and are unicellular or multicellular. They are present in various environments such as marine water and freshwater. They are classified into macroalgae and microalgae and are used for various commercial purposes. They possess various advantages such as less toxicity, requiring low temperature for synthesis. The production of nanoparticles by algae involves three major steps, i.e., the algal extract is obtained by boiling or heating algae in an organic solvent or water for a fixed period. Then, molar solutions of ionic metal compounds are prepared. Lastly, the molar solutions of the ionic metal compounds and the algal extract solution are mixed and incubated under controlled culture conditions with continuous mixing or without mixing for a fixed period [108]. The production of metallic nanoparticles depends largely on the algal species being used and its concentration. The reduction of metal ions is carried out by various biomolecules, such as peptides, polysaccharides, and pigments. The aqueous solution of metal nanoparticles is capped and stabilized with the help of cysteine residues and amino groups present in different proteins or by polysaccharides having a sulfur group [109]. Production of nanoparticles using algae occurs at a faster rate as compared to the synthesis using other biological agents. Various seaweeds such as *Ulva fasciata*, *Sargassum wightii*, and *Chaetomorpha linum* have been employed to produce silver nanoparticles with various sizes and shapes (Table 3). Marine algae species are rarely studied for the production of nanoparticles. *Chlorella vulgaris* can bind to tetrachloroaurate ions firmly to reduce the bonding of gold to Au (0). Gold bound to the algal species was converted into a metallic state in almost 90% of cases, and gold crystals were deposited inside and outside the cells and they had icosahedral, decahedral, and tetrahedral structures [110]. Mata et al. [111] reported a reduction of Au (III) to Au (0) using the biomass of the brown alga *Fucus vesiculosus*, and the synthesized nanoparticles were spherical. Shakibaie et al. [112] used a marine green microalgae *Tetraselmis suecica* for the synthesis of gold nanoparticles and found that the synthesized nanoparticles were spherical with a size range of 51–59 nm. A study on the in vitro and in vivo synthesis of silver nanoparticles using *Chlamydomonas reinhardtii* was reported in [113]. It was found that the in vitro synthesis was slower and produced round-shaped nanoparticles 5–15 nm in size, whereas, in the case of in vivo synthesis, it was moderately faster and produced rectangular-shaped nanoparticles 5–35 nm in size [113]. A study reported the synthesis of silver nanoparticles using *Spirulina plantensis*, where the average size of the nanoparticles was approximately 12 nm [114]. Senapati et al. [115] reported the synthesis of gold nanoparticles using *T. kochinensis* and it was found that the size of the synthesized nanoparticles was 18 nm. A study reported that *Spirogyra submaxima* was able

to convert Au^{3+} to Au^0 ions, which means that they were able to synthesize gold nanoparticles that were spherical, hexagonal, and triangular-shaped with a size of 2–50 nm [116]. Suganya et al. [117] reported the synthesis of gold nanoparticles using *Spirulina platensis*, and they were uniform in shape with an average size of 5 nm. The *Amphiroa fragilissima* was used in a separate study for the synthesis of silver nanoparticles, and it was found that crystalline nanoparticles were produced. Arsiya et al. [118] used *Chlorella vulgaris* for palladium nanoparticle synthesis, and the synthesized nanoparticles were crystalline with a size range of 5–20 nm. Sanaimeh et al. [119] used *Sargassum muticum* for the synthesis of zinc oxide nanoparticles and evaluated its potential anticancer activity against liver cancer cell lines. A study reported the synthesis of silver nanoparticles using *Portieria hornemannii*, where the nanoparticles were spherical in shape with a size between 70 and 75 nm [120]. There are different shapes of nanomaterials are produced by differently bacterial synthesis (Figure 4).

Table 3. Nanoparticles synthesized from algae.

Source	Metal Involved	Size	Shape	References
<i>Sargassum</i> spp.	G	-	Hexagonal, triangular	[121]
<i>Sargassum wightii</i>	G	8–12	Thin planar structures	[109]
<i>Sargassum Wightii</i>	S	8–27	Spherical	[122]
<i>Gelidiella acerosa</i>	S	22	Spherical	[123]
<i>Stoechospermum marginatum</i>	G	18.7–93.7	Spherical	[124]
<i>Ulva fasciata</i>	S	28–41	Spherical	[124]
<i>Sargassum myriocystum</i>	G	10–23	Triangular and spherical	[125]
<i>Ulva reticulata</i>	S	40–50	Spherical	[126]
<i>Chaetomorpha linum</i>	S	3–44	-	[127]
<i>Gracilaria corticate</i>	G	45–57	-	[128]
<i>Bifurcaria bifurcate</i>	CO	5–45	Spherical	[129]
<i>Enteromorpha flexuosa</i>	S	2–32	Circular	[130]
<i>Prasiola crista</i>	G	5–25	Cubic	[131]
<i>Sargassum</i> Alga	P	5–10	Octahedral	[132]
<i>Caulerpa racemose</i>	S	5–25	Spherical	[133]
<i>Acanthophora specifera</i>	S	33–81	Cubic	[134]
<i>Isochrysis</i> sp.	S	98.1–193	Spherical	[135]
<i>Laurencia papillosa</i>	S	-	Cubic	[136]
<i>Spirulina platensis</i>	S	5–50	Spherical	[137]
<i>Caulerpa serrulate</i>	S	10	Spherical	[138]
<i>Botryococcus braunii</i>	S	40–100	Cubical, spherical, and truncated triangular	[139]
<i>Padina pavonia</i>	S	49.58–86.37	Spherical, triangular, rectangle, polyhedral, and hexagonal	[140]
<i>Gelidium amansii</i>	S	27–54	Spherical	[141]
<i>Padina</i> sp.	S	25–60	Spherical	[142]
<i>Gelidium corneum</i>	S	20–50	Spherical	[143]

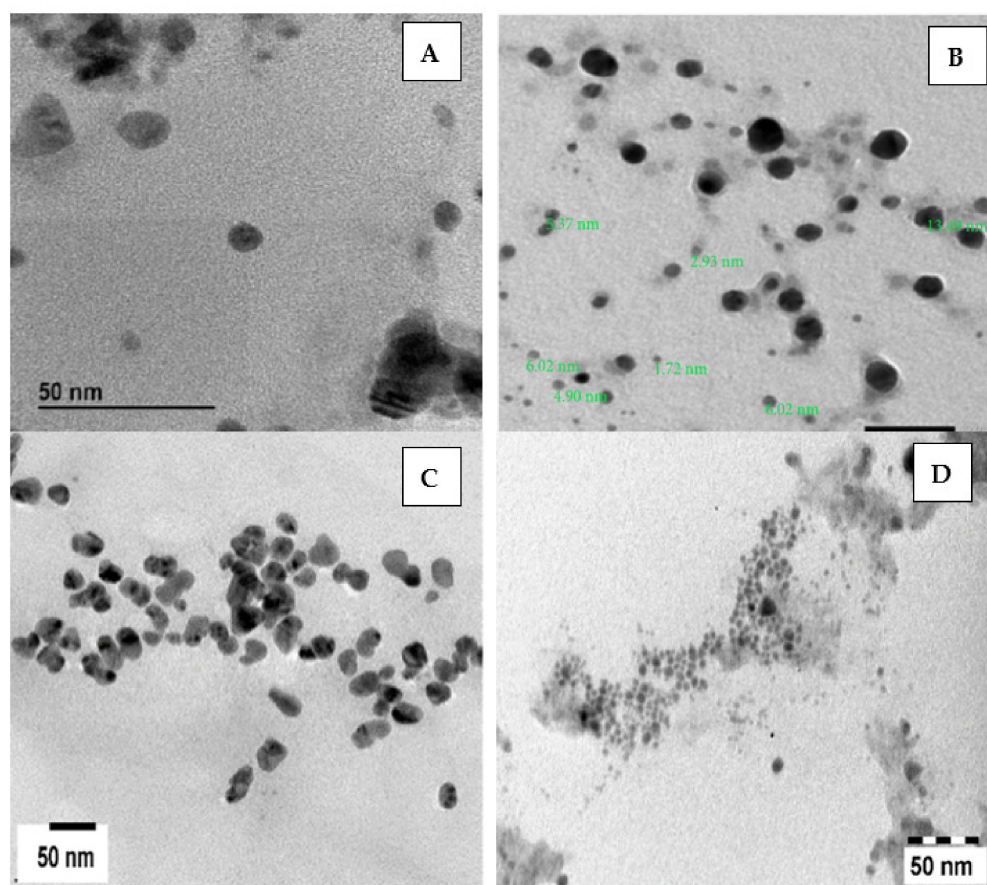


Figure 4. TEM images of different bacterial synthesized nanoparticles. (A) Silver nanoparticles (from *Pseudoduganella eburnea*); (B) copper oxide nanoparticles (from *Streptomyces*); (C) silver nanoparticles (from *Sargassum incisifolium*), and (D) gold nanoparticles (from *Sargassum incisifolium*) [144–146].

4. Applications of Nanomaterials/Nanocatalysts

4.1. Nanocatalysts in Biological Applications

Biologically synthesized nanoparticles have been extensively used in various applications (Figure 5). Silver and gold nanoparticles were also found to generally be used as antimicrobial agents against several microorganisms. They also possess anti-cancerous, anti-viral, antimalarial, and antifungal activities [1,3]. In addition to biomedical applications, they are also used in electronics, optics, cosmetics, coatings, sensing devices, therapeutics, environmental health, and chemical industries. [12]. They have appeared as a new drug delivery system for drug and gene transportation. A study reported that silver nanoparticles with a different shape can show varied antimicrobial activity due to their different surface area and active faces [147]. Mishra et al. [148] reported the synthesis of gold nanoparticles mediated by *Penicillium brevicompactum* and evaluated its potential role against mouse mayo blast cancer cells. Chauhan et al. [149] reported the synthesis of gold nanoparticles using *Candida albicans* and evaluated its anticancer potential against liver cancer cells. In another study, silver nanoparticles synthesized from *Stoechospermum marginatum* were used to evaluate the antibacterial activity against *Enterobacter faecalis*. It was found to have a higher antibacterial activity compared to tetracycline, whereas, in the case of *E. coli*, no positive effect was observed [124]. Soni and Prakash [150] used *Aspergillus niger* for the synthesis of gold nanoparticles and evaluated its anti-larval activity against *Anopheles stephensi*, *Aedes aegypti*, and *Culex quinquefasciatus*. It was observed that nanoparticles were more effective against *C. quinquefasciatus*. Sunkar and Nachiyar [151] reported the synthesis of silver nanoparticles from *Bacillus cereus*. It was found to have antibacterial activity against *S. aureus*, *K. pneumoniae*, *E. coli*, *S. typhi*, and *P. aeruginosa* [151].

Abdeen et al. [152] reported the synthesis of silver and iron nanoparticles using *Fusarium oxysporum* and evaluated their antimicrobial properties against *E. coli*, *Bacillus*, *P. aeruginosa*, *K. pneumoniae*, *Proteus vulgaris*, and *Staphylococcus* sp. A study reported the synthesis of silver nanoparticles using *Ulva lactuca* and found that at low concentration, it was able to inhibit the growth of *Plasmodium falciparum* [153]. A study reported the synthesis of selenium nanorods using *Streptomyces bikiniensis* and evaluated their potential anticancer activity against human cancer cells [154]. Borse et al. [155] tested the anticancer activity of platinum nanoparticles against MCF-7 and A431 cell lines, which were synthesized from *Saccharomyces boulardii*. Mohamed et al. [156] synthesized iron nanoparticles using *Alternaria alternate* and tested their antibacterial properties against *E. coli*, *B. subtilis*, *S. aureus*, and *P. aeruginosa*. It was found that iron nanoparticles possess the maximum inhibition of *B. subtilis*. In another study, *Streptomyces cyaneus* was used to synthesize gold nanoparticles and to investigate their anticancer activity against liver and breast cells. It was found that gold nanoparticles stimulated mitochondrial apoptosis, DNA damage, and induced cytokinesis arrest [157]. A study reported the synthesis of gold and silver nanoparticles using *Streptomyces* sp. and evaluated its potential antibacterial activity against *Salmonella infantis*, *S. aureus*, *Bacillus subtilis*, *Proteus mirabilis*, *K. pneumoniae*, *P. aeruginosa*, and *E. coli* [158]. Arya et al. [139] used *Botryococcus braunii* for the synthesis of copper nanoparticles and evaluated their antimicrobial activity. It was found to show toxicity against *E. coli*, *K. pneumoniae*, *P. aeruginosa*, and *S. aureus*. Husain et al. [159] reported that the synthesis of silver nanoparticles using cyanobacteria showed potential photocatalytic activity against dye. Dananjaya et al. [160] reported the synthesis of *Spirulina maxima*-mediated gold nanoparticles and evaluated its cytotoxicity and anticandidal activity. It was found that nanoparticles do not possess any cytotoxicity against cell lines, because they act as potent anticandidal agents. In a study, *Escherichia* sp. was used to synthesize copper nanoparticles and was utilized for the degradation of azo dye and textile effluent treatment. It was found that 83.90% of the congo red dye was removed and, in textile effluents, there was a significant reduction in electrical conductivity, pH, turbidity, total dissolved solids, total suspended solids, hardness, chlorides, and sulfates compared to nontreated samples [161].

4.2. Nanocatalysts in Dye Degradation

Due to the increasing population and use of dye in textiles, food, and other industries, the release of untreated waste into the water bodies is contaminating the environment at a rapid rate, due to which there is a growing demand for newer and more efficient technologies for the removal of these substances from the environment. Nanosized materials can be used to detoxify harmful organic and inorganic chemicals from the environment due to their ultrafine size, high aspect ratio, and interaction-dominating characteristics. Nanoparticles have generated a lot of interest due to their numerous uses in disciplines such as catalysts, detection, and environmental cleanup, such as the adsorption and degradation of different pollutants from liquid medium (Figure 6). Various bacterial and fungal species have been used for the synthesis of nanoparticles, and these synthesized nanocatalysts can be further used for the degradation of dyes (Table 4).

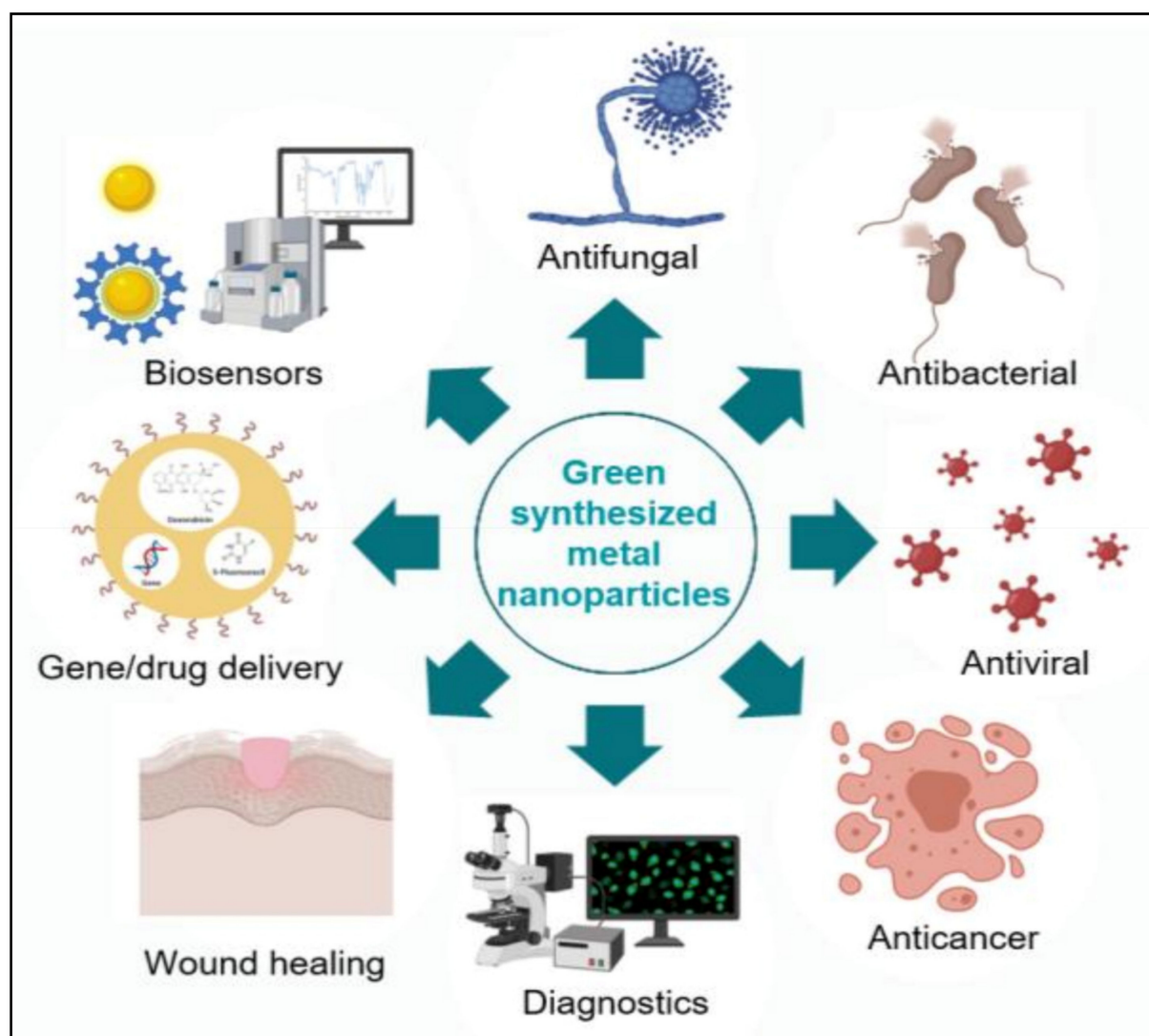


Figure 5. Biological applications of nanocatalyst [162].

Table 4. Degradation of dyes using bacterial-derived nanoparticles.

Dye	Nanoparticle Used	Synthesis of Nanoparticles Source	% Degradation	References
Malachite green	Silver	<i>Bacillus paralicheniformis</i>	90	[163]
Reactive black 5	Palladium	<i>Pseudomonas putida</i>	100	[164]
Methyl orange	Palladium	<i>Clostridium</i> sp.	90	[165]
Amaranth	Iron	<i>Shewanella decolorationis</i>	90.5	[166]
Methyl orange	Tin(IV) oxide	<i>Erwinia herbicola</i>	94	[167]
Congo red	Silver	<i>Pleurotus sajor caju</i>	78	[168]
Malachite green	Silver	<i>Acremonium kiliense</i>	95.4	[169]
Methylene Blue	Silver	<i>Saccharomyces cerevisiae</i>	80	[170]
Congo red	Silver	<i>Pestalotiopsis versicolor</i>	91.56	[171]
Direct blue 71	Palladium	<i>Saccharomyces cerevisiae</i>	98	[172]
Naphthol Green B	Iron-sulfur	<i>Pseudoalteromonas</i> sp. CF10-13	19.46	[173]
Bismarck brown	Zinc-oxide	<i>Aspergillus niger</i>	89	[174]
Methyl orange	Platinum	<i>Fusarium oxysporum</i>	-	[175]
Acid Brilliant Scarlet GR	Gold	<i>Trichoderma</i> sp.	94.7	[176]
Rhodamine B	Gold	<i>Cladosporium oxysporum</i> AJP03	-	[177]
Malachite green	Copper	<i>Escherichia</i> sp. SINT7	90.55	[178]
Rhodamine B	Gold	<i>Turbinaria conoides</i>	-	[179]
Malachite green	Silver	<i>Gracilaria corticata</i>	-	[180]
Methylene blue, rhodamine B, and methyl orange	Gold and silver	<i>Sargassum serratifolium</i>	-	[181]

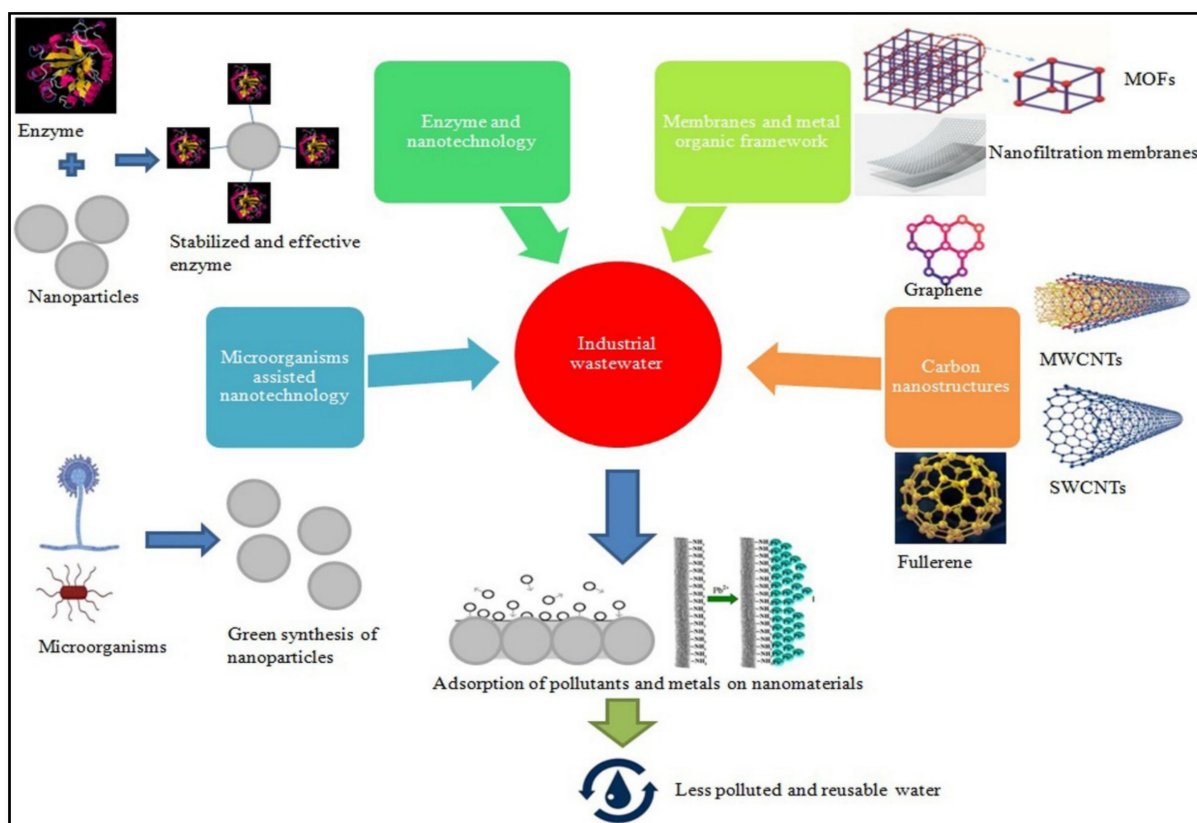


Figure 6. Remediation of industrial wastewater using a nanocatalyst [179].

4.3. Nanocatalysts in Heavy Metal Remediation

Heavy metals are detrimental contaminants that are toxic both in soluble and elemental forms. Diverse activities, including the development of industries, absurd waste management, defective landfill operations, and manufacturing and mining, lead to increased contamination of metals in soil and water [182]. The traditional method for heavy metal removal includes reverse osmosis, chemical precipitation, ion exchange filtration, evaporation, and membrane technology. However, the cost of these methods is occasionally higher; therefore, a cost-efficient and environmentally friendly method is of prime importance [183,184]. Various microbial-derived nanocatalysts have been reported to show remediated heavy metals (Figure 7). In a study, palladium nanoparticles were synthesized from *Enterococcus faecalis*, and these nanoparticles were used for the removal of hexavalent chromium from contaminated water. [185]. In another study, iron oxide nanoparticles derived from *Aspergillus tubingensis* were able to remove heavy metals such as copper 92.19%, nickel 96.45%, lead 98%, and zinc 93.99% from wastewater, and the reusability study showed that iron nanoparticles possess a high regeneration capacity [186].

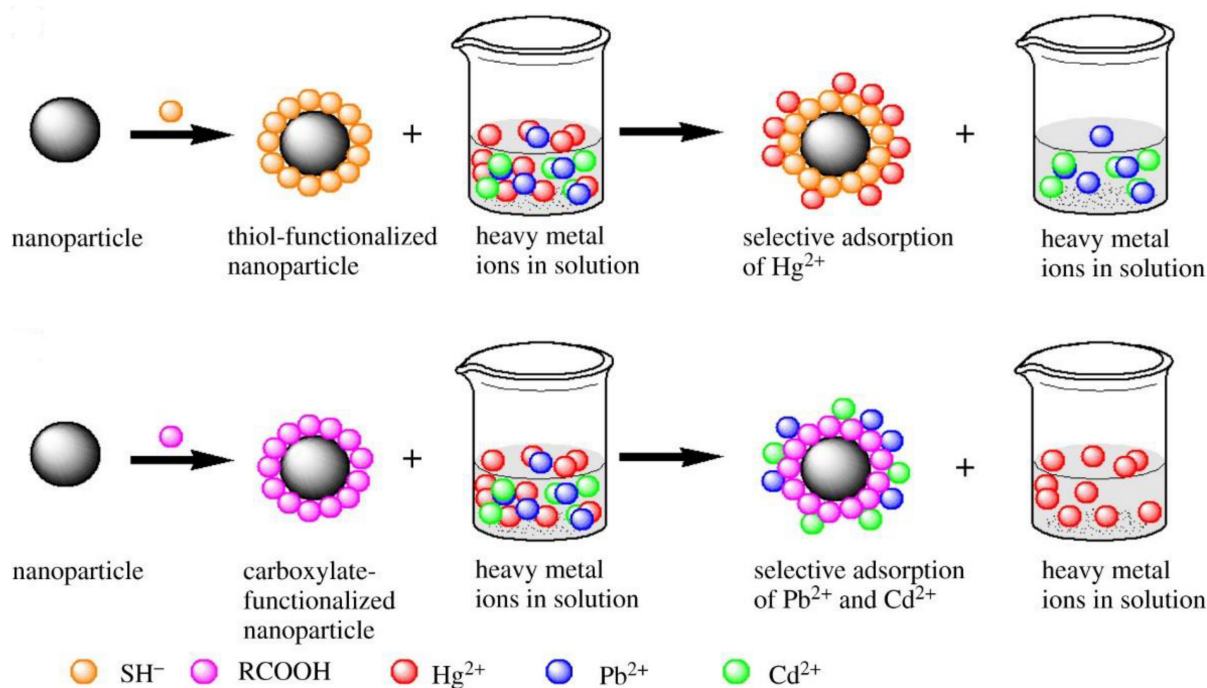


Figure 7. Nanocatalyst in heavy metal remediation [187].

5. Conclusions

The development of environmentally friendly and cost-effective techniques for producing nanomaterials and their concomitant applications in various fields is in great demand. Although a range of physical and chemical techniques have been found to be suitable for the synthesis of various nanomaterials, these methods show a nonnegligible concern because of the production of various toxic and nonbiodegradable by products. In this regard, the biogenic synthesis of nanomaterials offers an alternative solution to overcome the existing drawbacks that come from physical and chemical methods. The biological method offers a rigid control on the synthesized particles size and uniform shape, while the physical characteristics are retained at the same level as physical and chemical methods. Biologically synthesized nanomaterials are more prepared for biomedical application because of their lower toxicity. Nanomaterials provide various applications such as dye degradation, heavy metal remediation, and biological activity. However, in biological methods, many parameters affect the synthesis of nanoparticles, including pH, temperature, and whether they are manufactured internally or externally in the cell. These parameters should be studied in order to optimize the synthesis process. It is easy to manipulate bacteria genetically, whereas, in the case of fungi, the downstream process has been shown to be suitable for the large-scale production of nanomaterials. Regardless of the biological sources used, it is crucial to recognize the mechanism behind nanoparticle synthesis for maximum synthesis, which is important for commercialization purposes. Nonpathogenic sources are beneficial for the production of nanoparticles in an effective way. In addition, nanotoxicity should also be considered because it sometimes causes adverse effects on human health and animals. This can be tackled by the implementation of regulation and legislation, and researchers must conduct joint multidisciplinary studies in various fields of medical sciences, nanomedicine, nanotechnology, and biomedical engineering.

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