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Nanobioremediation: harnessing chemically modified and biogenic nanoparticles for environmental cleanup

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ABSTRACT

Due to widespread industrialization, urbanization, and modern agricultural techniques, an enormous number of pollutants are released into the environment. The contaminants can pollute air and water, threatening the ecosystem. It is challenging to get rid of these harmful pollutants from the environment. Recently, bioremediation aided by nanotechnology is the most promising method for cleaning up harmful pollutants due to its economical and promising advantages. Nanoparticles and their composites have a high surface-to-volume ratio and have a quick capacity to interact with diverse particles, making them a desirable tool in a variety of applications. Chemically synthesized nanoparticles with enhanced properties, e.g., reactivity, catalysis, and adsorption, have been the subject of significant interest. Nanomaterials made of gold, aluminium, zinc, titanium, and cerium have been acknowledged for their effectiveness and safety in the environment. Microbe-mediated nanoparticle synthesis has recently gained attention as it exhibits exceptional properties to make sustainable nanocomposites. Bacteria, algae, fungi, viruses, actinomycetes, and their extracts have been utilized as catalysts to create non-toxic, pure, and environmentally safe nanoparticles for the reduction of metals. Nanoparticles that are mediated by both chemicals and microbes can effectively target pollutants for bioremediation with an emphasis on environmental clean-up. In this review, the significance, advantages, and applications of biogenic synthesized nanoparticles, as well as modified and optimized nanoparticles mediated by chemicals and metals, were thoroughly examined for the removal of heavy pollutants. The importance and sustainability of this new nanobioremediation approach was also discussed.

1. Introduction

Water is a vital component for maintaining life on earth. With the rise of industrialization, water resources are exploited and facing immense pressure, resulting in increased contamination. Annually, millions of tons of pollutants are

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discharged into water bodies. Thus, water purification from contaminants is a critical step in ensuring sustainability. Hazardous materials like pesticides, azo dyes, antibiotics, carcinogenic chemicals, byproducts, and other waste from manufacturing units, as well as radioactive elements like cobalt-60, radium-226, strontium-90, cesium-137, and Uranium from nuclear plants and research institutes, are among the pollutants that contaminate water [1]. These pollutants have a detrimental effect on the quality of water and its life. Conventionally, diverse electrochemical, sophisticated oxidation, and valorization techniques have been used to lessen the toxicity of wastewater effluents and to make their use more sustainable [2].

The marriage of nanotechnology with pollutant remediation is essential to replace expensive and complex procedures. Nanoremediation routes have advantages over other techniques due to their tiny size, high ratio of surface area to volume, catalysis actions, and simple process of production [3]. Due to the diverse properties of nanomaterials, they can efficiently remove contaminants from water and soil. Researchers are now interested in synthesizing significant nanoparticles (NPs), utilizing more straightforward and effective methods due to the novel applications of NPs in various industrial fields. *The Agency for Harmful Substances and Disease Registry* (ATSDR) notes that heavy metals like arsenic, mercury, lead, and cadmium are typically found in soil worldwide and are very toxic to both humans and crops. The ecosystem, climate, and human health are now being challenged by their levels and duration, which have grown significantly in recent years [3,4]. Over the last decade, the use of nanoremediation approach has become increasingly popular and can be accomplished through utilizing various materials such as metal and its derivatives, silica, carbon, nanotubes, polymers, and graphene-based materials, illustrated in Figure 1, to remove pollutants from both soil and water [3,5]. Therefore, new nanomaterials with improved features, such as high removal efficiencies or adsorption capacities and easier and less expensive production, are required for environmental remediation.

The integration of nanoparticles and bioremediation results in a powerful method for pollution removal, capitalizing on biogenic sources for the synthesis of nanomaterials and enabling the efficient elimination of pollutants at substantial levels [6]. Biogenic mediated synthesis of nanoparticles primarily utilizes micro-organisms such as bacteria, algae, fungus, actinomycetes, and plants by extracellular as well as intracellular synthesis. This approach leads to the development of an eco-friendly, feasible, efficient, and reliable system that can abate pollutants easily. Moreover, it serves as an alternative conventional method and promotes green and sustainable technology as it generates a negligible amount of sludge to treat contaminated sites. The production of nanomaterials through biogenic methods primarily uses metal-based nanoparticles and their composites because of their vast range of applications, uses, and properties. The market for these metallic nanoparticles is projected to reach an astonishing 50 billion dollars worldwide by 2026 [6–9].

Figure 2 illustrates the process of microbe-based biogenic synthesis of various nanoparticles, their characterization, and the various ways in which they can be applied. The main focus of this review is on the chemogenic and biogenic synthesis of nanoparticles and their impacts, as well as the various applications of different types of nanoparticles in a wide range of industries, primarily in the field of remediation. Additionally, it explores future prospects of this technology.

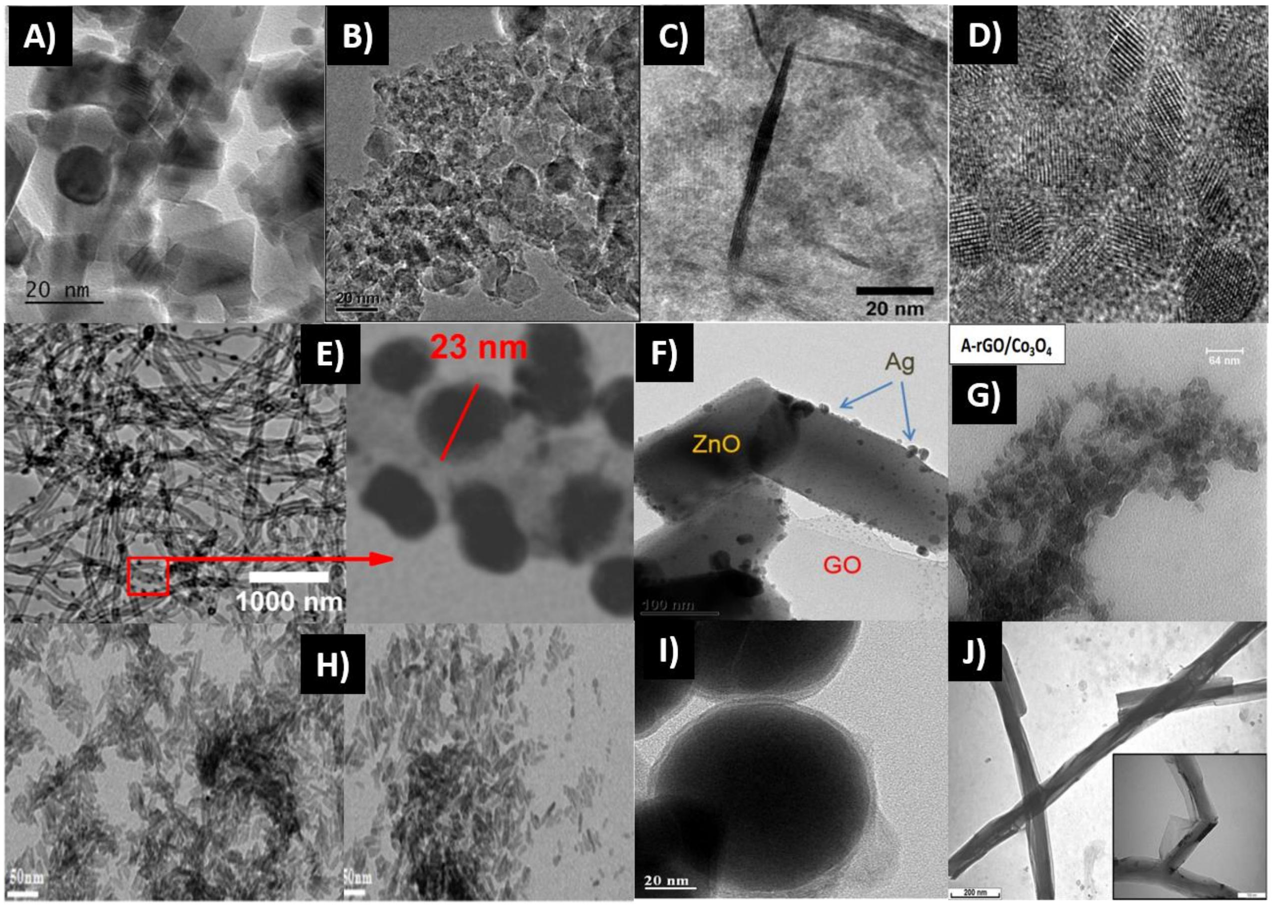

Fig. 1. Morphological analysis of Nanomaterials by TEM; A-CeO_2 [81], B-NF-TiO_2 [49], C-Iron-oxyhydroxide@COF [60], D-GO Sheets (5nm) [63], E-Ag CNT [88], F-Zno/Ag/GO composite [170], G-A-rGO/CO_3O_4 [141], H-Apatite Monolith [90], I-nZVI [173], J. MWCNT [130]; Adapted by Creative Commons license and Permissions.

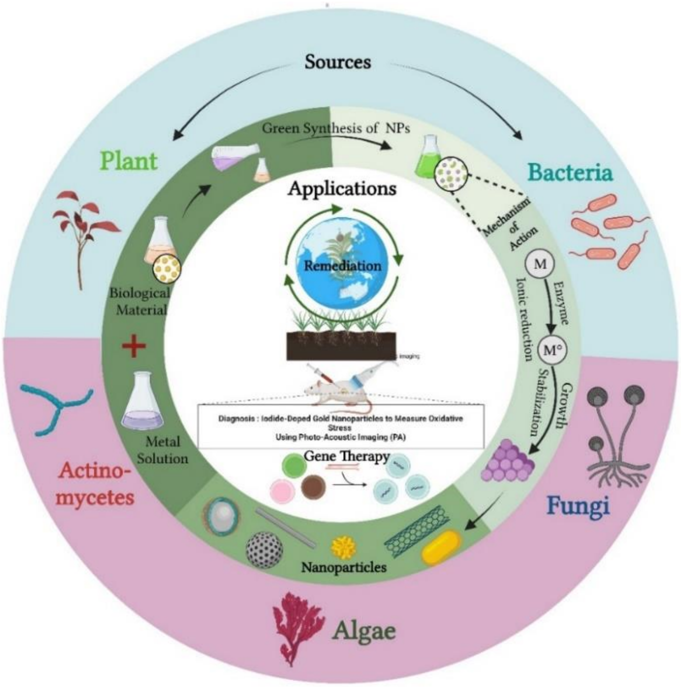

Fig. 2. Schematic representation of sources of biogenic mediated NPs and its synthesis process. Created with Biorender.com

2. Nanomaterials and their applications

Nanotechnology is a rapidly developing and innovative field that encompasses a diverse range of disciplines such as biology, chemistry, and material science. Given its vast potential and cost-effective nature, the utilization and advancement of nanotechnology is being actively explored and developed in the recent decade. Nanomaterials possess exceptional imperium, such as the high surface area to volume, size ranges between (1-200 nm), prolonged stability, ease of doing in surface engineering, and biocompatibility, which makes an impact in every field of applications. Applications of nanoparticles are not limited to nanotechnology but it is also applied in the field of drug delivery, where NPs are used as a transporter, cosmetics, agriculture, biomedical, nano-sensors, wound healing, biofuel, petroleum, and remediation [7,8,10,11]. Studies reported that various types of drugs like Rutin [12], Salinomycin [13], Hesperetin [14] are being transported to specific cancer sites by engineering nanoparticle surfaces with both polymers and antibodies to eradicate mighty cancer and its stem cells. NPs are also used in the bio-imaging of tissues or organs by the theranostics approach in humans as well as lower animals [15]. Moreover, siRNA is encapsulated inside nanoparticles to reduce the level of gene expression used as targeted gene therapy [16]. The integration of nanotechnology in modern-day agricultural systems and practices is emerging as a revolutionary approach to minimize the waste of fertilizers and its impact on human health and the environment. Various research has been conducted on the use of nano-sized pesticides, fungicides, and fertilizers, including the bioremediation of xenobiotics, to enhance plant health management and soil improvement [17].

2.1 Application of NPs in cancer therapy and diagnostics.

India is renowned for its rich tradition of herbal medicine. A significant proportion of these drugs belong to the flavonoid class, which is a highly potent candidate to eradicate cancer; however, the challenge lies in targeted delivery and minimizing damage to healthy tissues [18,19]. Breast cancer is the leading cause of death among women globally, with roughly 15% of cases being classified as triple-negative breast cancer [20]. In recent years, liposome-based nanoparticles have gained widespread popularity as a means of enhancing the effectiveness of drug delivery across various routes of administration. Additionally, they are non-cytotoxic and stable over a long period of time [21]. Nanoparticles not only have the capability to deliver drug molecules but also have the potential to deliver siRNA to specific tissues not limited to cancer. [22] demonstrated that the silencing of the *luc2* (luciferase) gene by its siRNA and target specificity was achieved by the conjugation of aptamer, which will bind to the CD44 ligand to the surface of the liposome in the breast cancer cell line. Liposome nanoparticles have demonstrated promising outputs in imaging technology by transporting potential agents for imaging and therapy in biomedical sciences [23]. Multiple contrasting agents (CAs) are commonly utilized in radiological and nuclear medicine, which enhances the image of quality of non-invasive methods. The radiological CAs used for magnetic resonance imaging (MRI) include iron oxide, manganese-based, Gadolinium-based, and iron-platinum CAs. For X-ray-computed tomography (CT), iodine-based, lanthanide-based, bismuth, gold, and other metals are used as CAs. Phospholipids with sulfur hexafluoride, octafluoropropane, or perfluorobutane are used for ultrasonography (USG) [23–25].

2.2 Application of NPs in agriculture

Agriculture and its practices are the primary junction between humans and the environment, significantly contributing to changes in soil and the ecosystem. Although chemicals are widely utilized, losses due to pathogens, animals, and weeds directly result in a yield reduction ranging from 20 to 40%. Soil fertilization is a key aspect of contemporary organic agriculture. However, it is significantly inefficient and results in a considerable amount of waste. By taking advantage of encapsulation technology of drugs or molecules, it can be applied in the field of agriculture [21,26,27]. The use of fertilizers and chemicals to enhance crop yield is on the rise globally in order to feed the increasing population, however, the waste generated by this process is also substantial [28]. It was extensively studied that nanoparticles like silica [29], selenium [30], gold [31], silver [32], copper [33], manganese [34], copper oxide and zinc oxide [35] and hydroxyapatite [36] are used in various applications in agriculture [26] such as fertilizer and growth stimulant [37,38] which showed the promising potential of nanoparticles in enhancing crop production compared to traditional fertilizers. Nanocalcite mixture containing 40% of $CaCO_3$, 4% nano SiO_2, 1% MgO and 1% Fe_2O_3 not only improved the uptake of essential minerals such as Ca, Mg and Fe, but also significantly enhanced the uptake of Phosphorous and trace minerals like Zn and Mn [39]. It has been found that nanoformulation of Fe/SiO_2 promotes germination as well as growth in barley and maize [40]. They utilized as nanopesticide, [37] extensively highlights the strong potential of silver NPs in combatting various phytopathogens such as *Phoma, Botrytis cineria, Megnaporthe grisea, Fusarium culmorun* and *Biplaris sorokinniana* etc. Furthermore, the nanoformulation of hexaconazole has been found to effectively eliminate pathogenic fungi such as red spider mite, *R. Solani, E. cichoracearum*. In the case of cucurbit mildew, the disease was completely eradicated through the use of silica NPs [26]. The use of nanoparticles in agriculture extends beyond just controlling plant diseases and improving growth and soil nutrients. It is vital to pick the appropriate NPs to ensure crop productivity, as not all NPs have been shown to be successful in enhancing plant growth and antifungal activity.

2.3 Application of NPs in food industry

In the current food and technology industries, efforts are being made to enhance or preserve the flavour, nutrient content, texture and especially the shelf life of food items. Nanoparticles are widely used for packaging and processing of it [41-43] excellently reviewed that the additions of enzyme encapsulations inside liposome based NPs such as proteinases and lipase to cheese-curd has been highly praised for improving cheese firmness by suppressing proteolytic activity and enhancing its elasticity and cohesiveness, adding value to the final product, cheddar cheese. The encapsulation of ascorbic acid within liposomes proved that the antioxidant activity of it was held at 50%, whereas it was lost in a free solution. [44] developed edible nanocoating size ranges nearly 5 nm for serving as nano-barriers against gas and moisture, additionally, they can enhance the taste, colour, and antioxidants values in fruits, vegetables, foods, and bakery products. Titanium as well as silicon dioxide nanoparticles were utilized as food additives in huge quantities [45]. Silver is considered as an antimicrobial agent by eliciting reactive oxygen species from silver zeolite utilized in maintaining life of food for prolonged time [46], but silver nanocomposites remain dominant over silver zeolite. The use of nanoparticle and its composites in the food industry extends beyond packaging and processing and includes their application as sensors for detecting human pathogens, pesticides, and other substances. However, there are some drawbacks to using NPs, including difficulties with large-scale production, high cost, and limitations in technology scalability, stability issues with NPs, and the need for effective sterilization methods [41–43].

3. Pollutant remediation by chemogenic Nanoparticles

The widespread use of nanoparticles has been implemented for the elimination of various toxic pollutants, including radioactive substances, azo dyes, antibiotics, heavy metals, and pesticides from both groundwater and soil (Table 1) [1,4].

Table 1. Chemogenic Nanomaterial for various pollutant

Pollutant	Nanomaterial Applied	Source of Pollutant	Removal Effectiveness	Reference
1,4-Dioxane				
1.	Nitrogen and Fluorine co-doped with TiO_2	Industrial	~100%	[49]
2.	Au-TiO_2	Commercial	59%	[50]
3.	GO/Fe_3O_4 doped into Ti_4O_7	Groundwater	85.4%	[51]
4.	nZVI (Zero Valent Iron	Groundwater	55%	[52]
5.	nZVI (Zero Valent Iron	Wastewater plant	99.9%	[53]

Pollutant	Nanomaterial Applied	Source of Pollutant	Removal Effectiveness	Reference
6.	nFe_3O_4/biochar	Commercial	98%	[54]
Arsenic				
1.	nZVI (Zero Valent Iron	Groundwater	~ 87%	[52]
2.	nZVI (Zero Valent Iron	Prepared by $NaAsO_2$	99.9%	[55]
3.	Magnetite	Prepared by $NaAsO_2$ and $Na_2\,HAsO_4.7H_2O$	As^{+3} – 87% As^{+5} – 98%	[57]
4.	Magnetite	River water	48.26%	[56]
5.	Ascorbic acid coated Fe_3O_4	Prepared by $NaAsO_2$ and $NaAsO_4.12H_2O$	As^{+3} – 16.56 mg.g^{-1} As^{+5} – 40.06 mg.g^{-1}	[58]
6.	(Pd) Palladium	Prepared by $NaAsO_2$	99.8%	[59]
7.	Iron-oxyhydroxide@COF	Commercial	98.4%	[60]
8.	Cerium(IV)-Incorporated Zirconium Oxide Nanocomposites	Prepared by As_2O_3	17.07 mg.g^{-1}	[61]
9.	Magnetite-maghemite	Prepared by As_2O_3 and As_2O_5	As^{+3} – 94% As^{+5} – 96%	[62]
10.	Graphene oxide sheets	Prepared by As_2O_3	105 mg.g^{-1}	[63]
11.	Fe_3O_4 – Boron Nitrite Sheet	Prepared by $NaAsO_2$	30 mg.g^{-1}	[64]
12.	Fe_3O_4	Commercial	As^{+3} – 188.69 mg.g^{-1} As^{+5} – 153.8 mg.g^{-1}	[65]
13.	Green Fe_3O_4	Prepared by $Na_2.HAsO_4.7H_2O$	As^{+5} – 39.84 mg.g^{-1}	[64]
Chromium (VI)				
1.	Magnetite-maghemite	Prepared by CrO_3	85%	[62]
2.	Nickel Ferrite	Prepared by $K_2Cr_2O_7$	89%	[67]
3.	polyvinylpyrrolidone-coated magnetite nanoparticles	Commercial	~100%	[68]
4.	Iron (Fe^0)	Prepared by $K_2Cr_2O_7$	100%	[69]
5.	Fe_3O_4	Prepared by $K_2Cr_2O_7$	38.47 mg.g^{-1}	[80]
6.	Cu/Fe Bimetallic Nanoparticles	Soil	84%	[70]
7.	Activated tyre particle	Prepared by $K_2Cr_2O_7$	96.5%	[72]
8.	SiO2/polyaniline composite	Prepared by $K_2Cr_2O_7$	99%	[73]
9.	Poly(4-vinyl pyridine) decorated magnetic chitosan biopolymer (VMCP)	Commercial	344.83 mg.g^{-1}	[74]
10.	MgO	Prepared by $K_2Cr_2O_7$	81.25%	[84]
11.	Scrap tire particles	Industrial Wastewater	92.3%	[71]
Lead (Pb)				
1.	Nickel Ferrite	Prepared by [Pb (NO_3)]	79%	[67]
2.	Copper Oxide (CuO)	Commercial	84%	[76]
3.	Hematite (α-Fe_2O_3)	Tap Water	100%	[86]
4.	polyvinylpyrrolidone-coated magnetite nanoparticles	Commercial	100%	[68]
5.	SnO_2	Prepared by Pb(NO_3)2	1265.8 mg.g^{-1}	[78]
6.	Copper oxide (CuO)	Commercial	88.4%	[77]
7.	Iron oxide/hydroxide	Commercial	~820 mg.g^{-1}	[79]
8.	Fe_3O_4	Prepared by Pb(NO_3)2	53.11 mg.g^{-1}	[80]
9.	carboxylate-ferroxane	Prepared by Pb(NO_3)2	94.79%	[79]
10.	CeO_2	Prepared by Pb(NO_3)2	189 mg.g^{-1}	[81]
11.	TiO_2	Prepared by Pb(NO_3)2	154 mg.g^{-1}	[81]
12.	Fe_3O_4	Prepared by Pb(NO_3)2	83 mg.g^{-1}	[81]
13.	T-Fe_3O_4	Prepared by Pb(NO_3)2	99 %	[82]

Pollutant	Nanomaterial Applied	Source of Pollutant	Removal Effectiveness	Reference
14.	Manganese ferrite	Commercial	~100%	[75]
15.	Tin Oxide (SnO_2)	Prepared by $Pb(NO_3)2$	1265.8 mg.g^{-1}	[78]
16.	Magnetite	Prepared by $Pb(NO_3)2$	99%	[3]
17.	Magnetite	River water	98.8 ±5.6 %	[56]
18.	Magnesium Oxide (MgO)	Commercial	94%	[85]
Nickel (Ni)				
1.	Polyvinylpyrrolidone-coated magnetite nanoparticles	Commercial	~100	[68]
2.	Fe_3O_4	Prepared by $Ni(NO_3)2{\cdot}6H_2O$	209.2 – 362.3 mg.g^{-1}	[91]
3.	Scrap Tire particles	Industrial Wastewater	95.9%	[71]
4.	Alumina	Prepared by $NiSO_4$ $6H_2O$	96.6%	[93]
5.	γ- Alumina	Prepared by $NiCl_2$ $6H_2O$	99.41%	[88]
6.	Multiwalled carbon nanotube	Prepared by $NiCl_2$ $6H_2O$	87.65%	[88]
7.	Copper Oxide (CuO)	Commercial	52.5%	[76]
8.	Iron Oxide (Fe_2O_3)	Commercial	97%	[90]
9.	Copper Oxide (CuO)	Prepared by $Ni(NO_3)2{\cdot}6H_2O$	15.4 mg.g^{-1}	[92]
10.	Magnesium Oxide (MgO)	Commercial	94%	[85]
Uranium				
1.	Hydroxyapatite nanoparticles	Prepared by $UO_2(NO_3)2$ $6H_2O$	310 mg.g^{-1}	[98]
2.	nZVI	Wastewater	98%	[96]
3.	nZVI	Prepared by $UO_2(NO_3)2$ $6H_2O$	100%	[95]
4.	nZVI	Commercial	99%	[97]
5.	Humic acid-coated Fe_3O_4	Seawater	39.4 mg.g^{-1}	[99]
6.	$Co_{0.5}Mn_{0.5}Fe_2O_4$	Commercial	104 mg.g^{-1}	[100]
7.	succinyl-β-cyclodextrin-APTES@maghemite nanoparticles	Prepared by $UO_2(C_2H_3O_2)_2{\cdot}2H_2O$	286 mg.g^{-1}	[101]
8.	polyamidoxime-functionalized nanoparticles	Prepared by $UO_2(NO_3)2$ $6H_2O$	247 mg.g^{-1}	[102]
9.	Amine-functionalized magnetic-chitosan	Prepared by $UO_2(C_2H_3O_2)_2{\cdot}2H_2O$	178 mg.g^{-1}	[103]
10.	Multiwalled carbon nanotube	Commercial	98%	[104]
11.	COOH-modified hollow tubular nanofiber	Prepared by $UO_2(NO_3)2$ $6H_2O$	99.25%	[105]
12.	SO_3H modified hollow tubular nanofiber	Prepared by $UO_2(NO_3)2$ $6H_2O$	97%	[105]
Methylene Blue				
1.	Vanadium Oxide (VO_2)	Commercial	235.7 mg.g^{-1}	[107]
2.	Serpentine decorated magnetic nanoparticles	Commercial	162 mg.g^{-1}	[114]
3.	GO supported Ni Nanoadsorbents	Commercial	946.1 mg.g^{-1}	[113]
4.	TiO_2-PVA nanocomposite	Commercial	97.1%	[115]
5.	TiO_2 – Poly nanocomposite	Commercial	99%	[108]
6.	Silica (SiO_2)	Commercial	80%	[109]
7.	Magnetite	Commercial	95%	[110]
8.	2D Magnetic Titanium Carbide	Commercial	94%	[120]
9.	Magnetic Iron Oxide	Commercial	94%	[111]
10.	Fe_3O_4	Commercial	100%	[112]
11.	Gg-cl-PAA/Fe_3O_4 nanocomposites	Commercial	719.4 mg.g^{-1}	[118]

Pollutant	Nanomaterial Applied	Source of Pollutant	Removal Effectiveness	Reference
12.	Magnetic multi-wall carbon nanotube	Commercial	15.74 $mg.g^{-1}$	[117]
13.	Rod Shaped silver nanoparticles	Commercial	1039 $mg.g^{-1}$	[116]
14.	$EuVO_4/g\text{-}C_3N_4$ Mesoporous Nanosheets	Commercial	~100%	[119]
Benzene				
1.	ZnO NPs coated on Zeolite	Synthetize	98.9%	[123]
2.	ZnO NPs coated on Activated carbon	Synthesize	98.2%	[123]
3.	Carbon nanotube	Commercial	987.5 $mg.g^{-1}$	[127]
4.	Magnetite	Commercial	77 $mg.g^{-1}$	[121]
5.	Fe_3O_4/ $AC@SiO_2$@Sulfanilamide	Commercial	557 $mg.g^{-1}$	[131]
6.	$Fe_3O_4/AC@SiO_2@1,4$-DAAQ	Commercial	1232.77 $mg.g^{-1}$	[132]
7.	nZVI	Commercial	97%	[126]
8.	Calcium peroxide	Groundwater	42.8%	[122]
9.	Cupric Oxide	Commercial	98.7%	[125]
10.	Calcium Peroxide	Commercial	100%	[124]
11.	Carbon NPs with hollow fiber membrane	Commercial	97%	[128]
12.	Copper Oxide	Commercial	68.4%	[125]
13.	SWCNT-MN	Commercial	98.6%	[129]
14.	Carbon nanotube decorated with silver NPs	Natural water	77.9%	[130]
Toluene				
1.	Fe_3O_4/ $AC@SiO_2$@Sulfanilamide	Commercial	612 $mg.g^{-1}$	[131]
2.	$Fe_3O_4/AC@SiO_2@1,4$-DAAQ	Commercial	1352.16 $mg.g^{-1}$	[132]
3.	nZVI	Commercial	97%	[126]
4.	Cupric Oxide	Commercial	92.5%	[125]
5.	Carbon NPs with hollow fiber membrane	Commercial	82.8%	[128]
6.	FeO-MWCNT	Commercial	63.34%	[135]
7.	GO NPs	Commercial	56%	[138]
8.	SWCNT-MN	Commercial	99.6%	[136]
Rhodamine-B				
1.	Modified Fe3O4 nanoparticles with humic acid	Commercial	98.5%	[139]
2.	$A\text{-}rGO/Co_3O_4$	Commercial	102.9 $mg.g^{-1}$	[141]
3.	Cu_2O	Commercial	95%	[142]
4.	$\alpha\text{-}Al_2O_3$	Commercial	100%	[143]
5.	Magnetic iron oxide nanoparticles	Commercial	98%	[140]

3.1 1,4-Dioxane

According to ATSDR, 1,4-dioxane (1,4-D) is a colourless organic heterocyclic ether that has a range of industrial applications. Neglected and poor waste management can lead to the release of this toxic substance into the environment, where it has a strong attraction. Its presence poses a threat to marine and aquatic life, and 1,4-dioxane is believed to be a potential carcinogen and endocrine disruptor [47,48]. [49] showed the combination of nitrogen and fluorine in TiO_2 nanoparticles is an effective and economical solution for removing 1,4-dioxane through solar photocatalysis, with results showing close to 100% removal. Gold nanoparticles with TiO_2 promoted degradation via photocatalytic process with effectiveness of 59% [50]. An 85.4% effectiveness to remove pollutant was observed by graphene oxide NPs engineered on Ti_4O_7 ceramic membrane, after 15 cycles, the membrane integrity was maintained by this approach [51]. [52] reported that 55% 1,4-dioxane was broken down through various radical mechanisms in the selective order of efficiency being persulphate, followed by hydrogen peroxide and then peroxymonosulphate (PS>HP>PMS) at a pH of 3 by nano zero valent iron NPs (nZVI). Similarly, nZVI was utilized by [53] and reported that light intensities infer removal of 1,4-D, after 6 h of irradiation 99.9% of pollutant was removed at 3.25 mW/cm^2 light intensity. The study reported that the combination of nano magnetite particles and biochar (nFe_3O_4/biochar) resulted in a removal rate of 98% for 1,4-D after period of 120 minutes [54].

3.2 Arsenic

In terms of environmental contamination and toxicity, arsenic (III and V), a metalloid present in food and the environment in the soil, air, and water, is a significant problem. Inorganic arsenic, which is highly poisonous, carcinogenic, and extensively absorbed by the body, is frequently discovered in drinking water. Zero valent iron NPs are frequently used in the removal of arsenic contamination in aqueous solution mimicking the contaminated water and in groundwater with a removal efficiency of 99.9% and 87%, respectively [52,55]. Magnetite-based nanoparticles were synthesized using an aerosol-assisted chemical vapour deposition method. The solution was transformed into aerosol, and then thermal energy was applied to produce a fine powder. After 15 mins, 87% of As^{+3} and 98% of As^{+5} were eliminated. The same type of NPs was used to test river water with arsenic contamination, showing 48.26% efficiency against removing pollutants [56,57]. [58] reported that Fe_3O_4 NPs surface engineered with ascorbic acid coating through the hydrothermal method was able to remove trivalent and pentavalent arsenic at 16.56 mg.g^{-1} and 40.06 mg.g^{-1} concentration, respectively. It has been reported that palladium-based NPs synthesized using the green algae method have proven to be one of the most effective means of removing arsenic from groundwater, with an efficiency rate of 99.8% at a concentration of 0.5 g/L. This process only takes 5 minutes, making it a quick and efficient technology [59]. Novel nanocomposites were synthesized by [60] in which they reported that 98.4% of trivalent arsenic was removed successfully by engineering the covalent organic frameworks NPs by lepidocrocite nanorods. This framework had the potency to adsorb mercury as well as lead in even harsh conditions. Cerium ions were coated on a nanocomposite of zirconium oxide, which removed pollutants at 17.07 mg.g^{-1} [61]. Combination of both magnetite and maghemite based NPs were synthesized and discovered to be more effective at pH 2 with adsorption capacity for trivalent and pentavalent ions of 94% and 96% respectively [62]. Interestingly, nano sheets are also in the race to remove pollutants, they were engineered by ferrous oxide ions with an adsorption capacity of 105 mg.g^{-1} [63]. Green iron oxide as well as chemogenic iron oxide NPs were synthesized to remove pentavalent arsenic 39.84 mg.g^{-1} and 153.8 mg.g^{-1}for pentavalent 188.69 mg.g^{-1} for trivalent arsenic contaminant [64,65].

3.3 Chromium

Chromium is a heavy metal, typically in the form of trivalent chromium (Cr III) and hexavalent chromium (Cr VI). Cr(VI) is widely used in industries to manufacture products like paint, steel, alloys, and chrome, as well as in wood treatment [66]. Combination of two different types of NPs was reported that can remove 85% of the pollutant [62]. 89% of chromium was eliminated by nickel ferrite NPs [67]. Studies by [68] and [69] reported a 100% elimination of contaminants by magnetite NPs with a coating of polyvinylpyrrolidone and iron NPs, respectively. The use of bi-metallic NPs made of copper and iron to remediate chromium is a promising solution. This technique involves transforming Cr (VI) into Cr (III) through co-precipitation and is effective to the tune of 84% [70]. Recently, an approach utilized waste materials such as activated tire particles and scrap tire particles. These materials exhibited high effectiveness in chromium removal, with reported rates of up to 96.5% and 92.3%. This method tackles chromium contamination and offers sustainable waste management [71,72]. A remarkable 99% and 81.23 % of the pollutant was removed by SiO_2/polyaniline nanocomposite and MgO nanoparticles [71,73]. Magnetic chitosan coated with 4-vinyl pyridine nano biopolymer effectively removed hexavalent pollutants at a 344.83 mg/g concentration [74].

3.4 Lead

Lead, a versatile metal used in construction, batteries, and more, poses health risks through water contamination and other sources. Its links to cancer remain inconclusive, yet exposure can harm immunity and increase mortality in animals. Removing lead from water is crucial for public health and groundwater quality [66]. Nickel ferrite nanoparticles show promise for environmental remediation due to their strong absorption, low conductivity, stability, and ferromagnetic properties, ensuring the effective removal of heavy metals without degradation. [67] reported that 79% of heavy metal contaminated water has been remediated to restore its quality to fresh water, and manganese ferrite can effectively remove 100% of lead contamination from aqueous solution [75]. Copper oxide nanoparticles are cost-effective and efficient in removing lead from water, with green synthesis methods investigated to ensure safety; they have an adsorption efficiency of around 84% and 88.4% [76,77]. In recent years, synthesizing metal oxide nanoparticles has intensified to enhance pollutant removal efficiency. Some of the most commonly used NPs in this endeavor include tin oxide, iron oxide/magnetite, cerium oxide, titanium oxide, magnesium oxide, and calcium oxide [78]. reported that 1265.8 mg.g^{-1} of pollutant removed from aqueous solution. 820 mg.g^{-1}, 53.11 mg.g^{-1}, 83 mg.g^{-1}, 99%, 98% and 99% of lead pollutant removed from mimic contaminated water by [79-82,56 and 83] respectively. The report by [81] says that, it was found that among the three different NPs tested, CeO_2 was the most effective option for removing lead contaminant, with a concentration of 189 mg.g^{-1} achieving the highest removal rate. [84,85] found that among the three different NPs tested, CeO_2 was the most effective option for removing lead contaminant, with a concentration of 189 mg.g^{-1} achieving the highest removal rate. The modified form of iron oxide NPs, hematite, successfully removed all traces of lead from tap water [86] and hematite NPs were surface engineered with polyvinylpyrrolidone coating also showed 100% removal of all lead [68].

3.5 Nickel

Nickel, a versatile transition metal, predominantly exists in its +2 oxidation state in nature and living organisms [87]. Nickel naturally occurs in surface water and soil, with human activities such as industrialization and agricultural practices increasing their concentration [88]. Establishing a safe level of nickel in water is challenging due to its carcinogenic properties. Workers in nickel refinery factories face increased risks of lung, nasal cavity, kidney, and prostate cancers compared to the general population [89]. [90], demonstrated that iron oxide NPs at a concentration of 40 g/L were highly effective in removing nickel from water, with a removal efficiency of 97%. Fe_3O_4 NPs removed contaminants in a range of 209.2-363.3 mg.g^{-1} [91]. CuO NPs were able to achieve a removal efficiency of 52.5% and a concentration of 15.4 mg.g^{-1}, useful for localized treatments [76,92]. As an alternative to other metal oxide NPs, magnesium-based oxide NPs have demonstrated exceptional removal efficiency for nickel contamination in water with 94% [85]. Polyvinylpyrrolidone was used to surface-engineer magnetite nanoparticles in order to maximize their ability to absorb and remove nickel contamination from water. The results showed this method was highly effective, with nearly all nickel contaminants being eradicated [68]. Alumina and γ- Alumina based NPs have been shown to be highly effective in eliminating nickel contamination in water. Both types of nanoparticles have demonstrated absorbance efficiency of 96.6 % and 99.41%, making them some of the most potent candidates for nickel removal [88,93]. It is not only spherical shaped NPs that are being used in the effort to remove nickel contamination, but multiwalled carbon nanotubes (MWCNTs) have also shown promise in removing nickel from water solution. [88] reported that MWCNT efficiently remove nickel with 87.65%.

3.6 Uranium

As society seeks economical, eco-friendly energy sources, nuclear energy gains attention for its reliability and low carbon footprint. Yet, uranium's biological toxicity remains a key challenge [94]. Illegal uranium waste harms ecosystems, contaminates soil and water, and endangers public health. Zero-valent iron is used to remove uranium from water. [95] reported that complete elimination of uranium from aqueous solutions was possible using nanoscale zero valent iron (nZVI) particles and their graphene composites through precipitation. This method effectively removed all traces of uranium, resulting in a purified solution. [96,97] also used nZVI nanoparticles effectively to remove uranium from wastewater, initially achieving a 98% removal rate, later improving to 99%. This highlights their strong potential for uranium elimination from contaminated water. This demonstrates the strong potential of nZVI NPs in the elimination of uranium from contaminated water. [98] reported that uranium remediation at a concentration of 310 mg.g^{-1}. The effectiveness of removing uranium from seawater using Fe_3O_4 NPs coated with humic acid was found to be 39.4 mg.g^{-1}[99]. $Co_{0.5}Mn_{0.5}Fe_2O_4$ based NPs showed efficient elimination of uranium pollutant with effectiveness of 104 mg.g^{-1}[100]. The extraction of uranium from wastewater by maghemite NPs grated by succinyl-β-cyclodextrin was found to be an excellent option. It demonstrates a high removal capacity of 286 mg.g^{-1} at pH 6 [101]. Polyamidoxime and amine functionalized chitosan based NPs showed high absorption efficacy toward uranium of 247 mg.g^{-1} and 178 mg.g^{-1} respectively [102,103]. Carbon-based materials like MWCNTs grafted by cellulose achieve exceptional uranium extraction rates, up to 98%, showcasing their potential in environmental remediation [104]. Modification of hollow tubular nanofibers with COOH and SO_3H resulted in exceptional uranium removal rates of 99.25% and 97%, respectively. These findings highlight the efficiency of modified nanofibers for uranium elimination [105].

3.7 Methylene Blue

Methylene Blue (MB), a cationic thiazine dye, is extensively used across industries for its stability and vivid colour. However, its persistence and potential carcinogenicity necessitate efficient removal from industrial effluent to mitigate its environmental impact [106,107]. [108] reported that the combination of TiO_2 and 3-chloro-2-hydroxypropyl methacrylate resulted in the creation of a highly efficient nanocomposite. This nanocomposite was able to eliminate an impressive 99% of MB in just 5 minutes at room temperature and remained 96% effective upon reuse. The specific efficiencies of each material were found to be 235.7 mg.g^{-1} for vanadium oxide [107], 80% for silicon dioxide [109], 95% for magnetite [110], 94% for magnetic iron oxide [111] and 100% removal from [112]. The remarkable dye removal capabilities of these materials showcase their potential for diverse applications. Graphene oxide supported nickel nano adsorbents, achieving a rate of 946.1 mg.g^{-1}, while novel serpentine decorated magnetic nanoparticles extracted MB dye at a rate of 162 mg.g^{-1} [113,114]. Mesoporous TiO_2 and polyvinyl alcohol nanocomposites, synthesized using a facile process, exhibited high effectiveness in treating MB dye. A 97.1% dye removal was achieved within eight minutes, highlighting the potential of combining inorganic and organic materials [115]. The utilization of two different NPs, namely chitosan and titanium oxide, resulted in the removal of 90.9% of MB dye from a solution by photodegradation. Researchers are exploring complex nanoparticle systems with associated materials to maximize dye absorption, signaling innovation for improved efficiency in remediation. 2D magnetic titanium carbide, Gg-cl-PAA/Fe3O4 nanocomposites, magnetic MWCNT, Rod shaped silver NPs, $EuVO_4/g\text{-}C_3N_4$ mesoporous nanosheets remove MB dye with efficiency of 94%, 719.4 mg.g^{-1}, 15.74 mg.g^{-1}, 1039 mg.g^{-1}, 100% respectively [116–120].

3.8 Benzene

Benzene, a highly flammable liquid with solvent properties, is widely used in industry and commerce. Despite its usefulness, it poses significant health risks, including cancer, and requires careful management to minimize its impact on human health and the environment [66,121,122]. Zinc oxide NPs were coated on two different materials, zeolite and activated carbon in order to do comparative studies of benzene removal, It was found that ZnO NPs coated on zeolite have slightly higher removal efficiency than activated carbon, with 98.9% and 98.2% respectively [123]. [122,124] reported calcium peroxide as an effective pollutant remover, with a reported initial benzene removal of 42.8% from groundwater using its nanoparticles. Further research achieved 100% benzene removal. Copper oxide and cupric oxide showed high effectiveness, reaching 68.4% and 98.7% removal, respectively

[125]. Magnetite based NPs removed strontium contaminants at a maximum concentration of 77 $mg.g^{-1}$ [121]. nZVI is found out to be efficient NPs that remove 97% benzene from aqueous solution [126]. Researchers are exploring complex systems of nanoparticles and associated materials, like carbon sheets and tubes, to maximize benzene absorption, showcasing a growing interest in innovative remediation solutions. Integration of these components aims to enhance effectiveness. Carbon nanotubes [127], carbon NPs with hollow fiber membrane [128], single walled carbon nanotube [129] and carbon nanotube surface engineered with silver NPs [130] are excellently enhanced the extraction capacity of NPs for benzene, with 987.5 $mg.g^{-1}$, 97%, 98.6% and 77.9% respectively. The combination of various materials to synthesize nanoparticles enhances their reduction capacity, considering that [131,132] reported that complex material like Fe_3O_4/ AC@SiO_2@Sulfanilamide is highly effective to remove all contaminants at 557 $mg.g^{-1}$ and Fe_3O_4/AC@SiO_2@1,4-DAAQ NPs shows efficiency at 1232.77 $mg.g^{-1}$.

3.9 Toluene

Toluene is a flammable solvent used in manufacturing that poses serious health risks, including neurological damage and cancer. Its release into the environment contributes to smog and ozone depletion, emphasizing the need for careful handling and mitigation measures [66,133,134]. Carbon-based nanoparticles and tubes are widely used to remove toluene contaminants from aqueous solution. Carbon NPs with fiber membrane eliminated 82.8% of contaminants from water sources [128]. The utilization of multiwalled carbon nanotube (MWCNT) is doped with FeO to enhance the absorbance efficiency of NPs, it is found that FeO-MWCNT removed 63.34% of the pollutant from water [135]. [136] reported that a high amount of absorbance was achieved by single-walled carbon nanotube (SWCNT), with the efficiency of 99.6%. In the last decade, various metal oxide NPs are utilized due to their phenomenal properties like stability, reduction rate, etc. Cupric oxide and nZVI NPs are used by [137] and [126] to achieve the maximum removal efficiency with 92.5% and 97% respectively. Graphene oxide NPs also showed potency of 56% to remove toluene pollutant from aqueous solution [138]. Complex NPs like Fe_3O_4/ AC@SiO_2@Sulfanilamide and Fe_3O_4/AC@SiO_2@1,4-DAAQ synthesized to increase the reduction rate of NPs, with high removal effect of 612 $mg.g^{-1}$ and 1352.16 $mg.g^{-1}$, respectively [131,132].

3.10 Rhodamine B

Rhodamine B (RhB) is a dye used in textiles but has health concerns due to its neurotoxic and carcinogenic effects. It is a fluorescent dye used in various scientific fields. RhB persists in the environment, accumulating in aquatic life and posing health risks in the food chain. Surface-modified iron oxide nanoparticles are being explored to improve RhB removal efficiency, which is crucial for preventing environmental damage.[139] demonstrated that 98.5 % of dye has been extracted from aqueous solution by iron oxide NPs with modification of humic acid to its surface. Magnetic iron oxide NPs can remove the RhB from water with an effectiveness of 98% [140]. Additionally iron and nickel oxide NPs showed 96.1% and 111 $mg.g^{-1}$ extraction efficiency of RhB pollutant. [141] demonstrated that use of graphene oxide and cobalt oxide NPs to form a nanocomposite, which efficiently removes dye at 102.9 $mg.g^{-1}$ concentration. Copper oxide NPs alone showed significantly high removal efficiency with 95% [142]. α-Al_2O_3 nano adsorbent was used to remove RhB contaminants from aqueous solution, the study showed that 100% removal of RhB was achieved [143].

4. Pollutant remediation by biogenic Nanoparticles

In comparison to chemical and physical processes, the synthesis of nanoparticles (NPs) from biological sources, like as bacteria, actinobacteria, yeast, fungi, algae, and plants, is thought to be safer. Bacteria can adapt to high metal ion concentrations and transform them into NPs through enzymatic reduction [7,8,144] (Table 2).

Table 2. Biogenic Nanomaterial for various pollutant

	Source	Pollutant	Nanomaterial Applied	Removal Effectiveness	Reference
Bacteria					
1.	*A. ferrooxidans*	Arsenic(III)	kaolin@Fe–Mn binary (hydr) oxides composites	62.92 mg.g^{-1}	[145]
2.	*Lysinibacillus sphaericus* RTA-01	Chromium (VI)	Magnetic Iron Oxide	1052.63 mg.g^{-1}	[146]
3.	*Shewanella*	Chromium (VI)	Iron Sulphide	565.6 mg.g^{-1}	[148]
4.	*Enterococcus faecalis*	Chromium (VI)	Iron Oxide	98.03 mg.g^{-1}	[147]
5.	*Bacillus subtilis*	Fluoride	Hydroxyapatite	97.26%	[149]
6.	*Pseudomonas aeruginosa JP-11*	Cadmium	Cadmium Sulphide	88.66%	[150]
7.	*Alcaligenes aquatilis*	Reactive Blue 220	$Ag_2O/AgO-TiO_2$	96%	[151]
8.	*Desulfovibrio vulgaris*	17β-estradiol	Platinum	94%	[152]
9.	*Desulfovibrio vulgaris*	sulfamethoxazole	Platinum	85%	[152]
10.	*B. thuringiensis* BRC-ZYR3	Uranium	Production of Nano-Uramphite	98.7%	[153]
11.	*B. thuringiensis* BRC-ZYR4	Uranium	Production of Nano-Uramphite	99.1%	[153]
Plant					
1.	*Tithonia diversifolia*	Methylene Blue	Zinc Oxide	186 mg.g^{-1}	[156]
2.	*Sapium sebiferum*	Methylene Blue	Palladium	90%	[157]
3.	*Lentinula edodes*	Methylene Blue	Zinc Oxide	90%	[155]
4.	*Sutherlandia frutescence*	Malachite Green	Cadmium Sulphide	91%	[159]
5.	*Olea europaea*	Nickel (II)	nZVI	97%	[160]
6.	*Amaranthus dubius*	Napthalene	ZnO-Fe	92.3%	[161]
7.	*Syzygium cumini*	Rhodamine B	Zinc Oxide	98%	[162]
8.	*Prangos ferulacea & Teucrium polium*	Arsenic	Iron	93.8%	[163]
9.	*Catharanthus roseus*	Chrominun	Silver	47.84%	[164]
10.	*Peltophorum pterocarpum*	Rhodamine B	Iron Oxide	95%	[164]
11.	*Clitoria ternatea Linn*	Malachite Green	Ag-ZnO	98%	[158]
Algae					
1.	*Halimeda gracilis*	Copper	Silver	85%	[172]
2.	*Microalgae*	Cadmium	MnS/FeS	648.6 mg.g^{-1}	[173]
3.	*Chlorella ellipsoidea*	Methylene Blue	Copper Sulphide	80.06	[169]
4.	*Chlorella*	Dibenzothiophene	Zinc oxide	97%	[174]
5.	*S. dimorphus*	Methylene Blue	ZnO Nanorod	100%	[170]
6.	*Spirulina platensis*	Methyl Orange	Iron Oxide	256.4 mg.g^{-1}	[171]
7.	*Spirulina platensis*	Crystal Violet	Iron Oxide	270 mg.g^{-1}	[171]
8.	*P. pavonica*	Total Nitrogen	Iron Oxide	89.8%	[175]
9.	*P. pavonica*	Total Phosphorous	Iron Oxide	93.96%	[175]
Fungus					
1.	*Purpureocillium lilacinum*	Navy Blue	Copper Oxide	57.5%	[177]
2.	*Purpureocillium lilacinum*	Safranin	Copper Oxide	63%	[177]
3.	*Aspergillus niger BSC-1*	Chromium	Iron Oxide	99%	[180]
4.	*Pycnoporus sanguineus*	4-nitroaniline	Gold	100%	[181]
5.	*Cordyceps militaris*	Methylene Blue	Zinc Oxide	97%	[179]
6.	*Dictyota dichotoma*	Green dye	Zinc Oxide	90%	[178]

4.1 Bacteria mediated NPs

Metal nanoparticles (NPs) such as Ag, Au, Cu, Se, and Fe, as well as metal oxide NPs like silver oxide (Ag_2O), copper oxide (CuO), zinc oxide (ZnO), titanium oxide (TiO_2), manganese oxide (MnO_2), magnesium oxide (MgO), and iron oxide etc. have all been produced by using bacteria as a biological nanofactory. It is not limited to only metal oxide NPs some other NPs are also synthesized by bacterial include hydroxyapatite, platinum and other composites. *A. ferrooxidans* is used to synthesize kaolin@Fe–Mn binary (hydr) oxides composites to extract the arsenic contaminations that are generally found in water bodies, with removal effectiveness at 62.92 mg.g^{-1} [145]. [146] reported that utilization of *Lysinibacillus sphaericus* RTA-01 bacterial strain synthesized the magnetic iron oxide NPs showed high efficacy for chromium remediation at 1052.63 mg.g^{-1}. Similarly, *Shewanella* and *Enterococcus faecalis* strain utilized to make iron sulphide NPs to eradicate chromium (VI) contamination from aqueous solution, with efficacy of at 565.6 mg.g^{-1} and 98.03 mg.g^{-1}, respectively [147,148]. Fluoride pollutant contamination was removed with 97.26% by hydroxyapatite NPs mediated from *Bacillus subtilis* [149]. 88.66% of cadmium contaminated water cleaned by *Pseudomonas aeruginosa* JP-11 mediated cadmium sulphide NPs [150]. Ag_2O/AgO-TiO_2 NPs were synthesized from *Alcaligenes aquatilis* to remediate reactive blue 220 dye, a study shows 96% removal of dye [151]. *Desulfovibrio vulgaris* strain was used to extract the 17β-estradiol and sulfamethoxazole contamination by platinum based NPs, with high efficiency of 94% and 85% respectively [152]. Nano uramphite was mediated by *B. thuringiensis* BRC-ZYR3 and *B. thuringiensis* BRC-ZYR4 to transform radioactive pollutant like uranium into uramphite, uranium which is highly hazardous to human health, with effectiveness of 98.7% and 99.1%, respectively [153].

4.2 Plant mediated NPs

Plant-mediated nanoparticle production is eco-friendly and sustainable, utilizing plant extracts for synthesizing various nanoparticles with reduced environmental impact [154]. Methylene blue is a heterocyclic dye that occurs in water bodies due to its wide use in the textile and food industry. It is remediated by zinc oxide and palladium based NPs that are synthesized from *Tithonia diversifolia*, *Sapium sebiferum*, *Lentinula edodes* to remove MB dye, with efficiency over at 186 mg.g^{-1}, 90% and 90% respectively [155–157]. Additionally, malachite pollutant removed with efficacy of 91% and 98% by cadmium sulphide NPs and Ag decorated zinc oxide NPs mediated by *Sutherlandia frutescence* and *Clitoria ternatea Linn*, respectively [158,159]. Nickel metal pollutant were remediated by nZVI mediated from *Olea europaea*, showed removal efficiency of 97% [160]. [161] reported that, they achieved 92.3% removal efficiency of Naphthalene by Zinc oxide NPs doped with iron which is prepared from *Amaranthus dubius*. Rhodmine B dye was extracted by zinc oxide NPs with efficacy rate of 98% from *Syzygium cumini* [162]. [163] reported that carcinogenic arsenic was removed by iron NPs with excellent efficiency of 93.8% from *Prangos ferulacea* & *Teucrium polium*. Chromium and Rhodamine B extracted by iron oxide based NPs with efficiency of 47.84% and 95% mediated from *Catharanthus roseus* & *Peltophorum pterocarpum* [164,165].

4.3 Algae mediated NPs

In the future, nanotechnology combined with phytoremediation will play a key role in environmental recovery, offering sustainable solutions. Microalgae, due to their unique properties, are particularly advantageous for nanoparticle synthesis, offering benefits over larger plants. Microalgae, such as Chlorella and Microsystis, are studied for their potential in bioremediation, utilizing their enzymes for converting contaminants into safer compounds extracellularly or intracellularly [8,166–168]. Noxious methylene blue dye was extracted by copper sulphide and zinc oxide NPs, with an efficiency rate of 80.06% and 100% mediated by *Chlorella ellipsoidea* and *S. dimorphus* [169,170]. *Spirulina platensis* utilized to synthesize iron oxide NPs to degrade harmful dyes like methyl orange and crystal violet, with efficiency of 256.4 mg.g^{-1} and 270 mg.g^{-1} [171]. [172] reported that 85% removal of copper from aqueous solution by silver NPs mediated from *Halimeda gracilis*. Cadmium was removed with an efficacy rate at 648.6 mg.g^{-1} by MnS/FeS NPs by *microalgae* [173]. *Chlorella* mediated zinc oxide showed 97% removal of dibenzothiophene [174]. Iron oxide NPs were utilized from *P. pavonica* against nitrogen and phosphorus, showed removal efficacy of 89.8% and 93.96% respectively [175].

4.4 Fungus mediated NPs

The growing use of fungi in nanoparticle (NP) production is driven by their efficiency in reducing metal salts to synthesize NPs. Fungi produce proteins and catalysts, facilitating rapid synthesis, while their resistance to metals and ability to accumulate them make them excellent NP candidates. This method yields NPs with specific sizes and shapes and holds promise for large-scale industrial production [8,176]. *Purpureocillium lilacinum* strain was used to extract the navy blue and safranin dye from aqueous solution by copper oxide NPs, showing effectiveness of 57.5% and 63% respectively [177]. Zinc oxide NPs were synthesized from *Cordyceps militaris* and *Dictyota dichotoma* to eliminate methylene blue and green dye, with efficiency of 97% and 90% respectively [178,179]. *Aspergillus niger* BSC-I strain was used to synthesized iron oxide NPs for remediation of noxious chromium with adsorption rate of 99% [180]. Gold NPs were mediated from *Pycnoporus sanguineus* with an absorption rate of 100% for 4-nitroaniline [181].

5. Artificial Intelligence and Machine Learning in nanobioremediation

AI is revolutionizing technology, including bioremediation, by aiding in nanoparticle design and environmental cleanup. Machine Learning forecasts nanomaterial characteristics and pollutant interactions, reducing trial and error. Predictive models simulate nanomaterial behaviour in varying conditions, enhancing remediation efficiency. AI accelerates nanoremediation development, though challenges like data availability and autonomous software persist. Overall, AI optimizes material design, process efficiency, and decision-making in nanobioremediation, improving environmental cleanup sustainability [182–184].

4. Conclusions

The remediation of toxic pollutants from the environment has become a crucial concern, and many methods have been developed to address the removal of hazardous and radioactive contaminants. The marriage of nanoscience and remediation/bioremediation could be a sustainable solution. The removal of toxic pollutants by chemogenic and biogenic synthesized NPs. Integration of NPs and micro-organisms opens new approaches for eco-friendly approaches to remediate pollutants. There is an urgent necessity of developing an economically effective, simple and efficient technique for removal of contaminants from polluted sites and bodies. Future research in nanotechnology and remediation could provide the high reactive composites by chemogenic method and in-depth mechanism of micro-organisms in remediation. Both approaches have advantages and disadvantages of their own, but they can be explored for large-scale remediation of contaminants.

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