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Removal of Heavy Metal Ions from Wastewater using Nanotechnology: A Review

Amritpal Singh S*[1], Sandhya Bharambhe[2], Pushpinder G. Bhatia[1]
*[1]Department of Physics, Guru Nanak College of Arts, Science & Commerce, Mumbai, Maharashtra, India
[2]Department of Physics, SIES Graduate School of Technology, Navi-Mumbai, Maharashtra, India

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ABSTRACT

Water pollution refers to the contamination of water sources by substances which make the water unusable for drinking, cooking, cleaning, swimming, and other activities. Pollutants include chemicals, trash, bacteria, and parasites. All these forms of pollution, directly or indirectly, make their way to water. Millions of people have lost their lives due to consumption of contaminated water. Due to rapid increase in population, development of new industries, there has been increase in water contamination. Major sources of water contaminants are in the form of organic pollutants, inorganic & biological pollutants. Inorganic pollutants include heavy metals like Pb, Cr, Cd, As, Cr, Hg etc. These heavy metals are harmful if consumed above their safety limits. Heavy metal-based industries have grown rapidly, and this has resulted in serious environmental problems with local dumping and wastewater from these industries. Nanotechnology is a rapidly expanding science with noteworthy outcomes in practically all areas of life. In recent years, active researchers are mostly interested in nanomaterials because of their distinctive characteristics, such as excellent reactivity and better catalysis. This review article, firstly, emphasizes on the methods employed for removal of Heavy Metal Ions from wastewater. Also, different types of nanomaterials used in the removal of Heavy Metal Ions & their future prospects are discussed further.

Keywords: Nanomaterial's, Heavy Metal Ions, Contamination, Magnetic nanoparticles, Wastewater, Adsorption

I. INTRODUCTION

Water can be contaminated by a variety of human activities or existing natural features, such as mineral-rich geologic formations. Chemical pollution from agriculture, industry, cities, and mining endangers the quality of the water[1]. These activities' air pollutants can also enter bodies of water via dry deposition, precipitation, and runoff. Some chemical pollutants have substantial and well-known health impacts, whilst many others have long-term health effects that are unknown[2]. Dangerous metals have contaminated the environment due to human progress and excessive activities, regardless of the fact the that these metals are naturally present in the earth's crust. The preservation of wood and dyes, the photochemical and steel industries, smelting, synthetic chemicals, coating, mineral extraction, atmospheric build-up, sewage irrigation, textiles, alloy fabrication, fertilizer production, and battery building are some of these operations[3]. Heavy metal contamination has increased substantially in recent years, owing to the ongoing development of urban, industrial, and agricultural activity[4][5]. In general, fertilizers, metallic ferrous ores, sewage sludge, pesticides, combustion of fossil fuels, and municipal wastes are the primary causes of heavy metal toxicity. Contaminated (also referred as waste) water has various forms of organic, inorganic & biological pollutants[6]. Herbicides and pesticides, medications, fuel (such as oil spills), industrial solvents and cleansers, and synthetic dyes connected with pharmaceuticals are all examples of organic pollutants in water[7]. Nutrients such as nitrate and phosphate, heavy metals, chloride, and radioactive isotopes released from mining or nuclear accidents (such as caesium, iodine, uranium, and radon gas) are examples of inorganic pollutants. Some nutrients can be derived from geologic material, such as phosphorus-rich rock, although they are most obtained from fertilizer, animal and human waste. Heavy metals such as arsenic, mercury, lead, cadmium, and chromium can bio accumulate and biomagnified throughout the food chain[8][9]. Pollutants from land cultivation, mining operations, agricultural chemicals, viruses & bacteria etc. are all pollutants present in water. Among the biological pollutants are Pathogens (infectious bacteria or viruses) enter water mostly through faecal waste from humans and animals due to insufficient sewage treatment[10]. *Fig. 1 shows the major pollutants present in water.* Many physiological and biological processes require trace levels of heavy metals as molybdenum (Mo), nickel (Ni), manganese (Mn), selenium (Se), zinc (Zn), magnesium (Mg), iron (Fe), chromium (Cr), copper (Cu), and cobalt (Co). Some trace metals are regarded vital, whereas others are deemed non-essential[11]. However, high amounts of these trace elements are detrimental to both individuals and the environment. High lead levels in drinking water have been linked to a variety of negative effects, including nervous system diseases, anaemia, renal failure, and cancer[12]. Due to their high toxicity, several metals, such as arsenic, mercury, lead, chromium, cadmium, are of utmost concern for public health because even little exposures can cause organ damage.[13]

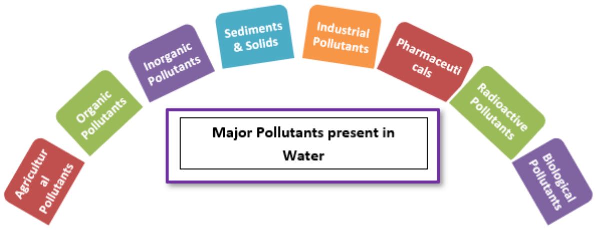

Fig. 1: Types of Pollutants in water

This review mainly focusses on heavy metals as pollutants in water bodies. Heavy metal Ions (HMI) in water are metallic elements that, when present in high concentrations, (density > 5 g/cm^3 i.e., 5 times more than density of water) can endanger human and environmental health[14][15]. Lead, mercury, and cadmium are examples of common heavy metals. There are permissible values below which the heavy metals in water are considered safe. According to Ministry of Jal Shakti, in India, Arsenic (As) & Lead (Pb) should not exceed 0.01 mg/L whereas for Cadmium (Cd) it is 0.003 mg/L & Chromium, (Cr) it is 0.005 mg/L, Copper (Cu) 0.25 mg/L, Nickel (Ni) 0.20 mg/L (1). According to the ministry reports, in 2021 it was found that these heavy metals exceed their permissible values & Arsenic (As) content in ground water in India is found in few Parts of 154 districts in 21 states & Union Territories (UTs), Lead (Pb) in parts of 92 districts in 14 states, Cadmium (Cd) in parts of 24 districts in 9 states, Chromium (Cr) in parts of 29 districts in 10 states. As per World Health Organisation's (WHO) report the permissible limits for As, Pb, Cd, Cr are 0.05, 0.05. 0.005, 0.05 ppm respectively[16]. (parts per million) *Fig. 2 shows various sources of heavy metal ions with their harmful impact on humans.*

Heavy metals disrupt the proper development and function of organs at concentrations greater than a few mg/L, poisoning the human body and destroying internal organs and tissues by diverse mechanisms such as enzyme denaturation, ion replacement, and protein inactivation[17]. Heavy metals have a variety of acute and chronic harmful effects on various human organs. In addition to neurological abnormalities, skin infections, vascular damage, immunological dysfunction, birth deformities, and cancer, heavy metal exposure can also cause problems with the kidneys and gastrointestinal tract.[18]. Exposure to high levels of heavy metals, particularly mercury and lead, can result in serious problems such as stomach colic pain, bloody diarrhoea, and kidney failure[19]. The fact that a number of metals have been identified as potential human carcinogens is yet another crucial component of long-term exposure.[20].

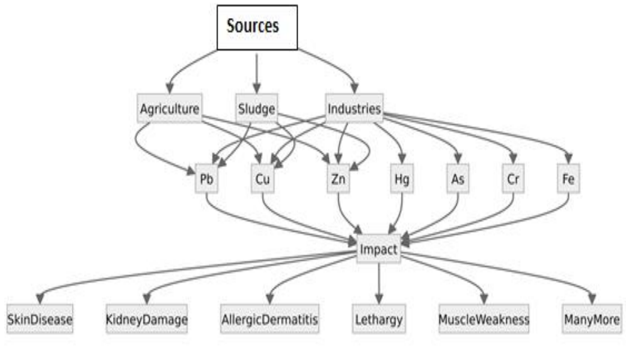

Fig. 2: Various sources of heavy metal ions with their harmful impact on humans.

II. METHODS ADOPTED FOR REMOVAL OF HEAVY METAL IONS FROM WASTEWATER

The most common ways for removing HMI from water are divided into three categories: physical, biological, and chemical procedures. The physical approach of wastewater treatment is primarily concerned with solid-liquid separations, and filtration plays a vital role.[21]. Chemical treatment methods rely on chemical interactions between contaminants and the operator of the chemical application to assist in either eliminating contaminants from water or neutralizing adverse effects connected with contaminants[22]. Although biological wastewater treatment appears simple since it depends on natural processes to aid in the decomposition of organic contaminants, it is quite complex. Adsorption is one the most useful and largely used technique. A great adsorbent for wastewater treatment should meet the following standards[23][24]:

1) Pollutants can be effectively removed from the surface.
2) Environmentally friendly
3) Recyclable.
4) Validate excellent selectivity and sorption capacity, particularly for low-concentration contaminants in water.

Each method is briefly described below. Their advantages & disadvantages are mentioned in Table 1. [25][26][27][28]

A. Physical Methods:

- Adsorption: Process where impurities in water are attracted to a solid surface.
- Ion exchange: Process that swaps ions in water using an exchanger.
- Nanofiltration: Filtration process that uses nanoporous membranes.
- Reverse osmosis membrane: Membrane process that uses pressure to push water through a semipermeable membrane.

- Solvent extraction: Process that uses a solvent to extract impurities from water.
- Ultrafiltration: Filtration process that uses a semipermeable membrane to remove large particles.

B. Chemical Methods:

- Coagulation & Flocculation: Process that initially destabilizes the collides by neutralizing the forces and then agglomerating the destabilized particles.
- Electrodeposition: Process that uses electricity to deposit a substance onto a surface.
- Electrodialysis: Process that uses electricity to drive the movement of ions through a membrane.
- Electrolysis: Chemical decomposition of water into hydrogen and oxygen using an electric current.
- Chemical precipitation: Process that uses chemicals like phosphates, sulphides, hydroxides to precipitate out impurities.
- Insoluble salt precipitation: Process that causes salts to form insoluble precipitates.
- Neutralization precipitation: Process that causes a chemical reaction to form precipitates.

C. Biological Methods:

- Bio-flocculation: Process that uses microorganisms to aggregate particles.
- Bio-sorption: Process that uses microorganisms to bind and remove contaminants from water.
- Phytoremediation: Process that uses plants to remove contaminants from soil, water, or air.
- Bio-precipitation: Process that uses microorganisms to precipitate out impurities.
- Biotransformation: Process that uses microorganisms to transform contaminants into less harmful substances.

These methods are used in various applications such as wastewater treatment, drinking water purification, and industrial processes.

Table 1: *The advantages & disadvantages of Physical, Chemical & Biological methods.*

Method	Advantages	Disadvantages	Reference
PHYSICAL METHODS			
1. Adsorption	• Cost effective • Easy availability of raw materials • Excellent removal efficiency • No generation of toxic elements	• Not suitable for automation • Regeneration of adsorbents	[29]
2. Ion exchange	• Can remove metals in low concentration • High removal efficiency is possible; Fast kinetics • Selective ion removal is possible using right ion exchanger	• Extremely sensitive to the pH of the solution • Has long production cycle	[30]
3. Nano filtration	• Can be operated continuously	• Low production volume • High pH requirements	[31]

Method	Advantages	Disadvantages	Reference
	• High rate of removal • High separation efficiency • Simple & Reliable		
4. Reverse Osmosis (RO)	• High efficiency in removal of ions • Water is used for drinking	• Backwash requirements • High cost • No regeneration	[32]
5. Solvent extraction	• Suitable for treating low concentrations of ions • High selectivity for specific ions	• Limited scalability for large scale applications • Adverse effect on environment due to used solvents & extraction by-products.	[33]
6. Ultra-filtration	• Easy separation of small sized particles/contaminants • Minimal use of chemicals; environment friendly	• High operational costs • Chances of membrane fouling • Limited removal efficiency	[34]
CHEMICAL METHODS			
1. Coagulation & Flocculation	• Efficient for wide pH range • Cost effective	• High operating cost of chemical addition • Large amount of sludge is produced • Not 100% efficient	[35]
2. Electro deposition	• Low cost • Less chemicals used • Selective process • Simple set-up	• Inclination towards non-conformal development on surfaces.	[36]
3. Electrodialysis	• Low operating pressure • Can remove metals in low concentration • Simple set-up	• Metal precipitation occurs • More energy consumption	[37]
4. Electrolysis	• High efficiency can be achieved	• Large operational cost • High energy consumption	[38]
5. Chemical precipitation (using hydroxides, sulphides etc.)	• Ease of operation; Cheap • Could be performed at suitable temperature • Can remove metals which are in high concentration • High selectivity	• High amount of precipitating agents are used • Large amount of sludge is generated • Does not remove complex metals	[39]

Method	Advantages	Disadvantages	Reference
		• Slow method	
6. Insoluble salt precipitation	• Effective removal • Cost effectiveness	• Sludge disposal • Selective precipitation	[40]
7. Neutralization precipitation	• Effective removal • Good pH adjustment	• Chemicals involved in huge amount • Limited applicability	[41]
BIOLOGICAL METHODS			
1. Bio flocculation	• Environmentally friendly • Cost effective	• Slow process	[42]
2. Biosorption	• Environmentally friendly • Cost effective	• Limited metal specificity	[43]
3. Photo remediation	• Environmentally friendly • Efficient removal of few ions	• Energy intensive • Limited depth of penetration	[44]
4. Bio precipitation	• Environmentally friendly • Low operating cost • Selective removal	• Limited scalability	[45]
5. Biotransformation	• Environmentally friendly • Efficient method	• Slow process	[46]

III.NANOMATERIALS USED FOR REMOVAL OF HEAVY METAL IONS

Zeolites are naturally occurring or synthetic hydrated aluminosilicate minerals with a porous structure[47]. These minerals have a three-dimensional crystalline structure with cavities and channels that can trap and exchange cations, water, and other molecules. Cost effectiveness, environmentally friendly, High efficiency are some of the advantages of using zeolites for removal of HMI's. *Fig. 3 shows different types of nanomaterials used for removing HMI from wastewater.* Zeolites are known for their high surface area, adsorption capacity, and ion-exchange properties, making them valuable in various applications such as: Adsorbents in wastewater treatment for removing pollutants & heavy metals. Due to their acidic property, they are also used as catalysts. Also used in gas separation techniques to remove or separate certain gases from a mixture. For cleaning purposes, they are also used in detergents. Zeolites are commonly used to remove heavy metal ions from wastewater due to their remarkable adsorption capabilities. These naturally plentiful minerals are very selective towards heavy metals. Zeolites' negatively charged frameworks enable the exchange of cations with heavy metal ions in water, making them efficient adsorbents[48]. Zeolites' adsorption ability for heavy metal ions can be enhanced by a variety of means, including the addition of surfactants or polymers. Studies have demonstrated that zeolites may successfully remove heavy metals such as lead, copper, cadmium, zinc, and nickel from industrial effluent, greatly improving water quality for agricultural usage[49]. Furthermore, thermal activation of natural zeolites increases their adsorption efficacy for certain heavy metals, making them a cost-effective and environmentally benign solution for water filtration. [50][51] N. Elboughdiri et al. [52] reported use of natural zeolites for adsorption behaviour of Cu, Pb & Cd in synthetic wastewater. Natural zeolites like clinoptilolite, chabazite, mordenite, jordanian and other varieties are recognized for their ion-exchange and adsorption properties, rendering them effective for the elimination of heavy metals. The key findings regarding the adsorption behaviour of Cu (II), Pb (II), and Cd (II) using natural zeolites are : The study indicated the suitability of zeolite for the removal of Cu (II), Pb (II), and Cd (II) ions from synthetic wastewater. Factors influencing the rate of adsorption include adsorbent mass, initial solution concentration, initial solution pH, adsorbent particle size, and agitation speed. It was observed that the removal efficiency of Cu(II) increased with increase in adsorbent mass, initial solution concentration, initial solution pH. It was also observed that the adsorption capacity of the adsorbents for heavy metals is directly related to the mass of absorbent, initial solution pH, agitation speed, and initial solution concentration. Z. Z. Tasic et al. [53] reported that natural zeolites have been found effective in removing organic compounds, HMI, from wastewater. Clinoptilolite shows good selectivity & sorption for metals like Ni, Fe, Pb in wastewater. Chabazite isa one of the most common zeolite used in removing HMI. The most frequent natural zeolites include analcime, chabazite, clinoptilolite, erionite, mordenite, and phillipsite. Clinoptilolite stood out among them as it is commonly used as an adsorbent for wastewater purification. Because of their strong adsorptive capabilities, they may effectively remove various pollutants like heavy metals, oil, and organic contaminants. Natural zeolites are low-cost adsorbents with high selectivity for different cations and ion exchange capacity. T.P Belova [54] reported model solutions with concentrations ranging from 0.5 to 3.5 mg-eq/L were used in removing HMI using zeolites. The sorption capacity of zeolite rises with metal ion concentration. The sorption capacity of heavy metal ions increases in the following order: $Cu^{2+} > Fe^{2+} > Ni^{2+} > Co^{2+}$. Langmuir and Freundlich equations were used to calculate sorption properties for each ion under study. [55]

Fig. 3: Types of nanomaterials used for removing HMI from wastewater

Carbon nanotubes (CNTs) are allotropes of carbon & are widely used to remove heavy metal ions from wastewater due to their superior physicochemical features. CNTs have a vast surface area, nanoscale size, and a variety of functions, making them extremely effective at adsorbing heavy metals[56]. Functionalizing CNTs with organic ligands improves their metal ion removal effectiveness by up to almost 100%. Furthermore, CNT composites including metal nanoparticles, graphene oxide, and zeolites have exhibited exceptional potential for removing heavy metals from wastewater due to their increased active surface area and adsorption sites[57]. The usage of CNTs and their composites not only aids in environmental monitoring and pollution control, but also in metal recovery and enrichment, emphasizing their importance in tackling heavy metal contamination in water. Functionalized multiwalled carbon nanotubes (MWCNTs) have been successfully utilized for the adsorptive removal of heavy metals like Pb2+ from synthetic wastewater, displaying high sorption capacity and efficiency[58]. The treatment of CNTs with active groups boosts their sorption ability and selectivity, making them useful in isolating and preconcentrating Pb(II) from complicated matrices. Furthermore, the use of CNTs as adsorbents for heavy metals such as hexavalent chromium, lead, manganese and cadmium has been studied, suggesting their potential for water purification. Overall, CNTs provide a cost-effective and efficient option for removing heavy metal ions from wastewater, thereby dramatically improving water quality[59].

Ibrahim Elghamry and colleagues [60] discovered a new substance called 2-aminobenzimidazole, which is based on a heterocyclic molecule. It was anchored and connected directly to MWCNTs-CO_2H through the carbonyl group utilizing simple procedures. The material was examined for its ability to adsorb hazardous metal ions, including Cd^{2+} and Pb^{2+}, from contaminated water solutions. Abdel Majid Adam and collaborators [61] found that crushing fullerene CNTs with the $ZnFe_2O_4$ composite improved the adsorption characteristics of free fullerene CNTs towards the tested heavy metal ions by 25%. Mostafa R. Abukhadra et al. [62] developed kaolinite nanotubes (KNTs) and described them as an adsorbent for metal ions such as Zn^{2+}, Cd^{2+}, Pb^{2+}, and Cr^{6+}. The synthesized KNTs effectively eliminated metal ions five times, resulting in significant reductions in removal percentages of 20.5%, 15.12%, 22.8%, and 23.16% for Zn^{2+}, Cd^{2+}, Pb^{2+}, and Cr^{6+}, respectively. Inadequate functional groups in raw CNTs cause easy aggregation, poor water dispersion, and insufficient metal adsorption capacity and selectivity. Adsorption efficacy of CNTs can be increased by adding functional groups such as hydroxyl, carboxyl, amine, and amino, all of which have strong chemical and electrostatic interactions with heavy metals. The aforementioned purification techniques can introduce oxygen-containing groups; however they may cause structural damage and reduce CNT stability. O^2-plasma oxidization has been demonstrated to be an effective, efficient, and environmentally friendly alternative approach for adding hydrophilic carbonyl and carboxyl groups without producing obvious structural damage[63]. Furthermore, it was revealed that -COOH can boost Pb(II) adsorption via ion exchange and surface precipitation, resulting in 93% elimination at pH 2.

Polymer based Nanomaterials: Heavy metal ion removal from wastewater has showed great potential for polymer-based nanomaterials. These materials have benefits including strong sorption activity, stability, and affordability. They include polymer nanocomposites and sorbents. These polymer-based materials have improved qualities such as improved permeability and antibacterial capabilities by integrating nanotechnology. These materials are now useful instruments in water remediation procedures due to their modification with additives such as metal nanoparticles, activated charcoal, and nano-fillers, which has increased removal efficiency. The advantages of polymer-based nanomaterials for removing heavy metal ions are:

(a) Efficient Adsorption: Polymer-based nanomaterials have excellent adsorption effectiveness for heavy metal ions in wastewater, which improves removal procedures.

(b) Tailored qualities: These nanomaterials can be designed to have specialized qualities for removing heavy metal ions with greater efficiency and selectivity.

(c) Regenerability: Polymer-based nanocomposites have a high degree of regenerability, which is important for practical wastewater treatment applications.

(d) Cost-Effectiveness: When compared to other technologies, polymer-based nanomaterials can provide a less expensive alternative for removing heavy metal ions from wastewater.

(e) Environmental friendliness: The usage of polymer-based nanoparticles is ecologically friendly, in line with the demand for sustainable and eco-friendly wastewater treatment methods.

Research has indicated that polymer nanocomposites are a useful tool for the adsorption of heavy metals from contaminated water, including Cr $^{3+}$, Ni $^{2+}$, Zn $^{2+}$, Cd $^{2+}$, Cu $^{2+}$, Hg, and Pb $^{2+}$. For example, [64] the production of polymeric nanocomposites such as HNTs@PDA/ZIF-8 has shown efficient adsorption capabilities for heavy metal ions, with amounts of 285.00 mg/g for Cu $^{2+}$ and 515 mg/g for Pb $^{2+}$. Furthermore, heavy metal ions from wastewater have been effectively removed by the use of nanofiltration (NF) membranes, which can be made from cutting-edge materials like glutaraldehyde (GA) and polyvinyl amine (PVAM) [65]. Additionally, using a carbon magnetic nanocomposite as an adsorbent has demonstrated excellent removal efficiency for zinc, lead, and copper ions, with lead adsorption capacities reaching as high as 83.54 mg/g. These investigations demonstrate how well polymer-based nanoparticles extract heavy metal ions from tainted water sources. A special sulphur-rich microporous polymer with a sulphur content of 31.4 weight percent can be used to extract mercury from water. It has a high concentration of easily accessible sulphur atoms and a large surface area. The as manufactured polymer (SMP) for Hg2+ shown significant binding affinity, high adsorption capacities, fast adsorption kinetics, and outstanding recyclability. The adsorption capacity of SMP is 595.2 mg/g. Ibrahim Hotan Alsohaimi & group [66] showed that the adsorption capacity of the composite (which consisted of a chitosan-polymer) for Pb $^{2+}$ ions increased as the pH increased until it reached pH 5.5. The maximum adsorption capacity was observed at an initial Pb^{2+} level of 20 mg/L and a contact time of 150 min.

Silica-based nanomaterials have demonstrated promising performance in the removal of heavy metal ions from wastewater. These nanomaterials, created using diverse approaches such as sol-gel procedures and surface modifications, have significant adsorption capabilities for metals such as lead, chromium, cobalt, and manganese[67]. According to studies, silica-based nanoparticles are effective at removing hazardous metals due to the presence of Si-OH groups on the surfaces, as well as their porosity and large surface area. However, material aggregation remains a concern for scientists, which can be solved by surface modification techniques such as functionalizing silica materials with nanoparticles. The functionalization of silica with various groups increases its adsorption efficacy, making it a long-term solution for water clean-up[68]. Studies have shown that these materials are effective at removing heavy metals using kinetic and equilibrium models, with spontaneous and thermodynamically beneficial adsorption processes. Furthermore, the recyclability and stability of silica-based nanoparticles have been emphasized, indicating their potential for repeated usage in heavy metal removal, hence contributing to environmental sustainability.

Several investigations [69] have demonstrated the efficacy of these materials in adsorbing contaminants such as Pb^{2+} and Cr(VI). The production of nano-silica oxide and mesoporous silica nanoparticles showed high adsorption capabilities for lead and cadmium ions, with removal efficiencies of up to 89%. Furthermore, the functionalization of silica nanoparticles with materials such as iron phthalocyanine and chitosan improved their adsorption capabilities, resulting in outstanding adsorption capacities of 150.33 mg/g for Pb^{2+} and 126.26 mg/g for Cd^{2+}. These important results highlight the potential use of silica-based nanoparticles as effective adsorbents for heavy metal removal in wastewater treatment applications. Nano-silica oxide (nano-SiO_2) has been successfully produced and used to adsorb lead Pb (II) and chromium Cr (VI) from aqueous solutions, with high removal efficiency.

Magnetic Nanoparticles (MNP's): Because of their efficacy and recyclability, magnetic nanoparticles are increasingly being used to remove heavy metal ions from wastewater. These nanoparticles, including magnetite nanoparticles, have excellent adsorption capabilities for heavy metals such as copper, lead, and zinc[70]. Functionalized magnetite nanoparticles can successfully remove heavy metal ions such as Pb^{2+} and Cd^{2+} from water, indicating potential adsorption capacities. Nanoparticles' unique qualities, such as a high surface-to-volume ratio and configurable band edges, allow them to effectively remove harmful contaminants from industrial and domestic wastes. Nano bioremediation, which involves microorganism-assisted nanoparticle synthesis, is a sustainable and environmentally benign technique to heavy metal removal, with benefits such as increased catalytic performance and cost-effectiveness[71]. Several studies have demonstrated the efficacy of various magnetic nanomaterials in adsorbing heavy metals such as copper, lead, zinc, chromium, and others from aqueous solutions. These magnetic nanocomposites, which include carbon magnetic nanocomposites, nanofiltration membranes, nanoparticles such as Ferrihydrite and magnetic iron nanocomposites, and iron oxide nanoparticles generated from coal fly ash, have shown excellent removal efficiencies ranging from 40% to over 99%. The usage of magnetic nanoparticles has advantages such as high adsorption capacities, quick kinetics, and easy separation from the solution, making them a promising solution for heavy metal wastewater treatment[72]. Spinel ferrite (SFs) are a significant class of ferric-ion-containing composite metal oxides with the general structural formula $M^{2+}Fe_2^{3+}O_4$ (where M = Mg^{2+}, Co^{2+}, Ni^{2+}, Zn^{2+}, Fe^{2+}, Mn^{2+}, etc.)[73]. They have exceptional magnetic properties, a high chemical stability, high specific surface area, tunable shape and size, surface active sites, and are simple to modify or functionalize. Chitosan-coated $MnFe_2O_4$ nanoparticles with uniform size displayed strong adsorption for Cu (II) and Cr (VI) at 22.6 mg/g and 15.4 mg/g, respectively[74]. A cobalt ferrite-chitosan-graphene composite was recently created using graphene and chitosan and it has a higher adsorption capacity of 361 mg/g for Hg (II) [75]. *Fig. 4 shows removal of HMI using magnetic nanoparticles.*

Muntean et al. [76] created a novel nanocomposite material from magnetic iron oxide, silver, and activated carbon by an innovative combustion method. The specific surface area of the nanocomposite (NC) is quite close to that of the activated carbon, but the significant advantage comes from its magnetic properties. The Langmuir model showed that the nanocomposite had maximal adsorption capacities of 81.36 mg/g for copper, 83.54 mg/g for lead, and 57.11 mg/g for zinc ions. M.M. Arman [77] used the citrate auto-combustion approach to create Ho-doped $SmFeO_3$ multiferroics in a single phase. This sample has the highest anisotropy constant and magnetization, making it ideal for applications including sensors, catalysis, and heavy metal removal. The Freundlich isotherm accurately reflects the adsorption of Cr^{6+} ions from water using Ho-doped $SmFeO_3$. Empirical studies published in the literature provides interesting scientific insights into the significantly varying characteristics of the adsorption kinetics of various adsorbate-magnetic nanoadsorbent combinations. For example, [78] depositing Ag ions onto Fe_3O_4 nanoparticles reduced particle size while improving the magnetic properties of the nanocomposites. In another investigation, a Fe^{3+} stabilized magnetic polydopamine composite displayed outstanding adsorption performance for methylene blue in single adsorbate aqueous solutions for pH ranging from 3 to 10 at 45 degrees Celsius. A study examined the effectiveness of magnetite particles in treating wastewater samples from a wastewater treatment facility. In general, magnetite particles had a promising behaviour in terms of reducing detergents and chemical oxygen demand, whereas removals of total nitrogen and phosphates, as well as most heavy metals examined (which included chromium, zinc, lead, copper, and cobalt), were high to moderate[79].

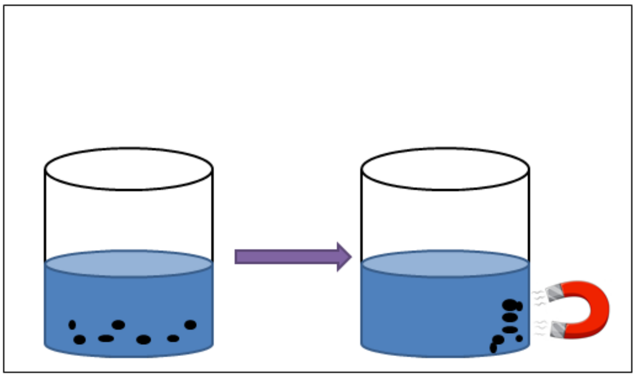

Fig. 4. Use of magnetic nanoparticles in removal of HMI from synthetic water

Due to restrictions on using bare hematite, magnetite, and maghemite nanoparticles, researchers typically create modified nanoparticles from iron oxide[80]. Over the years, nanoparticles have been synthesized using chemical processes such as coprecipitation, microemulsions, sol-gel synthesis, sonochemical reactions, hydrothermal reactions, hydrolysis, and so on. Furthermore, various factors influence nanoparticle size and stability, including pH and temperature. The methods described above could be used to create nanoparticles of various sizes and forms[81]. In order to produce pure synthetic materials, they are isolated using a magnetic field, washed multiple times with ultrapure water, and dried in a vacuum oven to eliminate diamines. To achieve optimal adsorption capacity, nanoparticles must be well-defined across several parameters. These criteria define and affect the application of nanoparticles, such as size, shape, size distribution, degree of aggregation, surface charge, and surface area. Christos Liosis and group [82] revealed the primary findings in the recent decade on the usage of magnetic nanoparticles. Metal oxide nanoparticles are synthesized from pure metal precursors. These nanoparticles have a wide range of applications in physics, chemistry, and materials research. Table 2 shows the usage of MNP to remove HMI from wastewater. Thermal elements are capable of manufacturing a diverse range of oxide compounds. These can have a variety of structural shapes, with an electrical structure that can exhibit insulator, semiconductor, or metallic characteristics. These nanoparticles have unique optoelectronic features due to their well-known localized surface plasmon resonance properties. Metal oxide nanomaterials include manganese oxides, nanosized iron oxides, titanium oxides, cerium oxides, zinc oxides, magnesium oxides, aluminum oxides, and zirconium oxides.

T. Naseem and colleague [83] presented a complete overview of five metal oxide nanoparticles: copper oxide, silver oxide, zinc oxide, iron oxide, and titanium oxide.

***Table 2:** Advantages & Disadvantages of using magnetic nanoparticles to remove heavy metal ions from wastewater:*[84]

Advantages	**Disadvantages**
High removal efficiency: Magnetic nanoparticles have been proven to remove heavy metal ions such as Pb and Cr with efficiencies ranging from 40-70%. Cost-effective: Iron oxide nanoparticles may be synthesized from waste materials such as coal fly ash, making it an inexpensive form of wastewater treatment. Iron oxide nanoparticles recovered from waste sources are reusable, giving them eco-friendly solutions for adsorption operations. Strong Adsorption Capacity: Magnetic carbon nanocomposites have shown strong adsorption capacities for metal ions such as copper, lead, and zinc, with removal efficiencies greater than 75%.	Fouling: Nanofiltration membranes, notably those containing nanoparticles, are susceptible to fouling, which can diminish their efficiency over time. Membrane Cleaning: Repeated cleaning of membranes affects their lifespan, providing issues for long-term use.

Graphene-based nanoparticles have emerged as powerful adsorbents for removing HMI from wastewater. These nanomaterials, which include graphene oxides and their composites, have high adsorption capabilities, chemical stability, and recyclability, making them ideal for water treatment applications[85]. Studies have demonstrated that graphene-based nanocomposites may effectively remove over 90% of heavy metal ions and synthetic dyes, with certain materials attaining up to 100% decontamination. Furthermore, density functional theory (DFT) studies have shown that nanographene is effective at capturing heavy metal ions such as Pb^{2+}, Hg^{2+}, and Cd^{2+} from wastewater, indicating its potential for practical applications in water treatment. Several studies [86] have demonstrated the efficacy of these materials. For example, graphene oxide (GO) functionalized with 3,5-diaminobenzoic acid (DABA) displayed improved adsorption performance for heavy metal ions such as $Pb^{2+}$and Al^{+3}, exceeding standard GO due to its large surface area and dentate functional groups. Furthermore, polyethyleneimine-grafted graphene oxide (PEI/GO) had a high adsorption capacity for lead ions (Pb^{2+}), with a maximum adsorption capacity of 64.94 mg/g, indicating that it is a viable adsorbent for heavy metal removal from industrial effluent. Furthermore, a long-lasting graphene-based water filter was created, capable of regenerating when treated with hot water or mild acid and eliminating heavy metals such as lead, cadmium, and mercury. These findings highlight the importance of graphene-based nanomaterials in sustainable heavy metal removal techniques. Graphene-based materials outperform typical materials in terms of heavy metal ion adsorption due to their high surface area, huge porosity, and functional groups. Graphene oxide typically interacts with heavy metals via precipitation, ion exchange, and surface complexation. Oxygen functional groups are commonly used to remove heavy metals due to their negative surface charge, which can effectively adsorb positively charged metals[87].

Nanophotocatalysts are sophisticated nanostructures utilized for heavy metal adsorption and photocatalytic reduction. They are often made up of semiconductor oxides such as titanium oxide (TiO_2), zinc oxide (ZnO), or binary nanomaterials that combine both oxides. When exposed to a suitable wavelength of light, nano photocatalysts induce photocatalytic ion reduction, which results in heavy metal removal from contaminated water[88].

Pollutants that are frequently encountered in wastewater along with heavy metal ions include polybrominated diphenyl ether, phthalates, phenolic chemicals, pharmaceuticals, antibiotics, and dyes. Metal-doping enhances the breakdown efficiency of several chemicals, including titanium, copper, zinc, and iron[89]. The efficiency of the photocatalyst is essentially determined by fundamental elements such as pH, doping, catalyst loading, light intensity, and stability. These factors contribute significantly to the degradation of contaminants. C. Sivaraman and group provides a detailed explanation of how these parameters affect photocatalytic degradation efficiency rates. Nanophotocatalysts' performance in heavy metal reduction can be improved through strategies such as dye sensitization, atom doping, defect introduction, and connecting multiple semiconductors[90]. The use of nanomaterials in photocatalysis provides physically and chemically customizable properties that improve heavy metal adsorption and ion reduction capabilities. The synthesis technique, surface area, defect concentration, and particle size all have an impact on nanophotocatalyst effectiveness, indicating the need for additional research to enhance their efficiency. Overall, nano photocatalysts offer a viable and environmentally benign solution to heavy metal contamination in water sources. Cheng et al. [91] employed a hydrothermal technique to create TiO_2/Fe_2O_3 hybrids, which were then used as a photocatalyst to degrade RhB.

Multifunctional nanoparticles (MFMNPs) are nanoparticles that have many capabilities within a single particle, making them useful for a variety of applications. MFMNPs are highly efficient at adsorbing heavy metal ions from wastewater due to their increased adsorption sites and active surface area[92]. These nanoparticles can have varying porosity, enabling for customisation based on particular removal needs. These nanoparticles serve an important role in human healthcare monitoring because they protect water quality and reduce the health hazards associated with heavy metal contamination. Magnetic nanoparticles can be functionalized with a variety of inorganic materials, including silica, metal oxides, and nonmetal compounds, to remove metals from water or wastewater. Coating nanoparticles with these materials stabilizes them in aqueous solution and enhances their binding to certain ligands on their surfaces[93]. They facilitate the covalent binding of ligands on the surface of nanoparticles. Traditional adsorbents, such as activated carbon, clays, silica beads, and biosorbent, have limitations in terms of permeability, selectivity, temperature dependence, pH dependence, and secondary waste. To avoid potential harm from harmful substances in the environment and biological systems, magnetic oxide nanoparticles must be released with precision and accuracy[94]. To prevent bursts and leaks, the superparamagnetic particles are coated to block undesirable potentials. Coating materials include: organic-inorganic shells (e.g., $Fe_3O_4@SiO_2$-NH_2) ; organic molecules (e.g., EDTAD- Fe_3O_4 , Fe3O4@C ; polymers (e.g., Fe_3O_4@APS@AA-Co-CA); metal oxides (e.g., MgO-Fe_3O_4) ; surfactants (Fe_3O_4-oleic acid); inorganic molecules (e.g., $Fe_3O_4@SiO_2$); and multi-shells ($Fe_3O_4@SiO_2$@CS@pyropheophorbide) . Ebenezer C. Nnadozie and team reviewed Multifunctional Magnetic Oxide Nanoparticle (MNP) Core-Shell[95].

Magnetic oxide nanoparticles (MIONs) are frequently used to shield the core magnetic component from weakening and improve stability in aquatic environments. Following thermalization, the protective coating acts as a sacrificial layer, providing additional functionality. Several authors employed silicon(IV) oxide in the form of tetraethyl orthosilicate (TEOS) for surface coating. Silicon(IV) oxide is frequently utilized for its chemical inertness, hydrophilicity, non-toxicity, and ease of modification. [96].

Multicomponent hybrid nanoparticles provide more active sites for heavy metal ion adsorption, resulting in larger adsorption capabilities. The use of various nanomaterials in multicomponent hybrids improves the effectiveness of heavy metal ion removal methods. The synergistic effects of diverse components in multicomponent nanoparticles can lead to better adsorption and photocatalytic reduction of heavy metal ions in wastewater[97].

L. Jiao and group studied and concluded that Halloysite@polydopamine/ZIF-8 nanocomposites effectively remove heavy metal ions. The parameters influencing heavy metal ion (Pb^{2+}, Cd^{2+}, Cu^{2+}, and Ni^{2+}) adsorption by HNTs@PDA/ZIF-8 were explored. The Langmuir model accurately described the adsorption of HNTs@PDA/ZIF-8. The maximum adsorption capacity was 285.00 mg/g for Cu^{2+}, 515.00 mg/g for Pb^{2+}, 185 mg/g for Cd^{2+}, and 112.5 mg/g for Ni^{2+} [98]. Furthermore, HNTs@PDA/ZIF-8 has a high regenerability, which is important in practical applications. The key interactions between adsorbents and heavy metal ions were discovered as electrostatic attraction, coordination processes, and ion exchange during the adsorption mechanism analysis.

Mantovani et al. [99] studied whether microalgae were suitable for the hydrothermal carbonization process, which is regarded as an environmentally acceptable method for producing iron nanoparticles. Laboratory tests demonstrated that microalgal biomass grown on municipal sewage sludge centrates can be used to manufacture iron nanoparticles for cleaning effluent. Marganovici et al. [100] investigated the chemical $Ca[O_2P(CH_2CH_2COOH)(C_6H_5)]_2$ (CaCEPPA), which has a layered structure with phenyl groups orientated into the interlayer space and crystallizes in the monoclinic system. The compound Co_2

$[(O_2P(CH_2CH_2COO)(C_6H_5)(H_2O)]_2 \cdot 2H_2O$ (CoCEPPA) has a 1D structure made of zig-zag chains. CaCEPPA and CoCEPPA materials were investigated for their ability to remove lead and cadmium from aqueous solutions.

Nanocomposite Membranes: Due to their superior characteristics and effectiveness, nanocomposite membranes play an important role in the removal of heavy metal ions from wastewater[101]. These membranes, which are frequently manufactured employing modern materials and modification processes such as interfacial polymerization, grafting, and the insertion of nano-fillers, have excellent treatment efficiency, reaching up to 99.90% for certain heavy metals such as Cr^{3+}. The addition of novel materials to the membrane structure, such as Zn-based metal-organic frameworks or functionalized halloysite nanotube nanoparticles, improves their effectiveness in heavy metal ion removal[102]. Furthermore, nanocomposite membranes have superior anti-fouling capabilities, higher water permeability, and high rejection rates for heavy metal ions, making them a suitable solution for effective wastewater treatment.

It is observed that Nanofiltration (NF) is a membrane-based separation technology that uses hydrostatic pressure to move molecules across semipermeable membranes. This approach permits low-molecular-weight solutes and solvents to pass through the barrier, while bigger molecules remain trapped[103]. NF has various advantages over other membrane technologies, including improved rejection of higher flux and divalent ions, less energy usage, and lower operating pressure. This technology may successfully remove oil, grease, suspended particles, heavy metals, dyes, and other contaminants from industrial effluents and drinking water. Membrane desalination, a highly efficient strategy for treating saline water and wastewater, has received a lot of attention recently.. The primary issue in membrane research is to develop highly permeable and stable membranes with outstanding selectivity and desirable physicochemical features[104]. A. A. Alotaibi and group reported that modifying mesoporous silica nanoparticles (MSNs) with amine and sulphonic groups improved the performance of mixed matrix polysulfone (PSU) nanocomposite membranes. Chemical alteration of MSNs improved membrane characteristics, resulting in higher water permeability[105]. The inclusion of functional groups on nanoparticles increased the efficacy of heavy metal ion removal, particularly cadmium and zinc. The elimination efficiency of these heavy metal ions increased by more than 90%.

The developed functionalized-MSNs/PSU nanocomposite membrane has excellent potential for industrial wastewater removal applications. It provides a viable alternative for the treatment of wastewater containing heavy metal ions. The study shown that using surface-functionalized mesoporous silica nanoparticles in membrane technology improves water treatment applications[106]. MoS_2 nanosheets of few layers were prepared through a surfactant assisted hydrothermal method. The prepared sheets were further used as an efficient adsorbent for removal of Hg from wastewater. The prepared nanosheets had high stability and negative zeta potential which made the material efficient for adsorption of mercury from wastewater. Novel 2D sheets made of graphene can be used as a very good adsorbent for the purification of heavy metals. Fu et al studied about the unique advances on 2D materials and also showed their composition and crystal structures .[107]

IV. CONCLUSION

Water is a crucial resource for life, yet maintaining its accessibility, affordability, and dependability is a significant challenge for our world. Heavy metal ions (HMIs) are among of the most hazardous contaminants. This review presents the use of nanotechnology and different types of nanomaterials used in removing heavy metal ions from wastewater. Each type of nanomaterials has some advantage and disadvantage depending upon its use. These different types of nanomaterials reported in literature are reported in this paper with few important results which are of great importance. As far as synthesis methods are concerned, this paper covers almost all types of physical, chemical and biological methods for synthesis of nanomaterials. Nanomaterials have potential for heavy metal removal from water due to some key physicochemical properties, such as larger surface areas than bulk particles, the ability to functionalize with different chemical groups to enhance their affinity to a given compound, and the ability to be reused multiple times. The preferential attraction of different heavy metals for the adsorbent determines their ability to be removed from water. Significant growth has been observed in use of adsorption method which produce great results.

V. FUTURE OUTLOOKS & CHALLENGES

The materials described above have limits regarding cost effectiveness and efficiency. The minimization of costs and environmental implications from waste products will be an important component to investigate for the widespread use of innovative materials in wastewater treatment. Although most novel materials have high adsorption performance in theoretical simulations, a large number of empirically manufactured novel materials are still required. Furthermore, considerable inconsistencies between practical and theoretical absorption capacities frequently result in non-ideal surface conditions, which appear to be a barrier to the widespread use of innovative materials in wastewater treatment. Some research found that modifying adsorbents improved their ability to remove heavy metals. Therefore, it is assumed that there are still numerous functionalized or modified new materials that are worth investigating in future.

More research on introducing easy synthesis methods to reduce costs, as well as investigating structural modifications by ligands, should be conducted. Cost-effective recycling techniques, environmentally friendly disposable options, and durability are also required for the practical application of innovative materials on a large scale. Clarification of the actual process causing the loss in performance following recycled usage is essential. Currently, no nanoparticles are environmentally friendly as well as non-hazardous. Their discharge throughout the synthesis, application, and disposal management processes can raise the risk of environmental contamination. As a result, there is an urgent need to establish a safe and appropriate method for their disposal. The development of more competent, low-cost, and recyclable nanoparticles may lead to safer water treatment in the near future.

VI.REFERENCES

1. G. Amo-Duodu, E. Kweinor Tetteh, S. Rathilal, and M. N. Chollom, “Synthesis and characterization of magnetic nanoparticles: Biocatalytic effects on wastewater treatment,” Mater. Today Proc., vol. 62, pp. S79–S84, 2022, doi: 10.1016/j.matpr.2022.02.091.
2. A. S. Mahmoud, M. K. Mostafa, and R. W. Peters, “A prototype of textile wastewater treatment using coagulation and adsorption by Fe/Cu nanoparticles: Techno-economic and scaling-up studies,” Nanomater. Nanotechnol., vol. 11, pp. 1–21, 2021, doi: 10.1177/18479804211041181.
3. S. Ethaib, S. Al-Qutaifia, N. Al-Ansari, and S. L. Zubaidi, “Function of Nanomaterials in Removing Heavy Metals for Water and Wastewater Remediation: A Review,” Environ. - MDPI, vol. 9, no. 10, 2022, doi: 10.3390/environments9100123.
4. K. Gupta, P. Joshi, R. Gusain, and O. P. Khatri, “Recent advances in adsorptive removal of heavy metal and metalloid ions by metal oxide-based nanomaterials,” Coord. Chem. Rev., vol.

445, p. 214100, 2021, doi: 10.1016/j.ccr.2021.214100.

5. J. Nikić et al., “Synthesis, characterization and application of magnetic nanoparticles modified with Fe-Mn binary oxide for enhanced removal of As(III) and As(V),” Environ. Technol. (United Kingdom), vol. 42, no. 16, pp. 2527–2539, 2021, doi: 10.1080/09593330.2019.1705919.
6. T. Patil, J. A. C. Eng, and B. B. T. Patil, “Journal of Advanced Wastewater Treatment Using Nanoparticles,” vol. 5, no. 3, 2015, doi: 10.4172/2090-4568.1000131.
7. F. M. Alzahrani, N. S. Alsaiari, K. M. Katubi, A. Amari, F. Ben Rebah, and M. A. Tahoon, “Synthesis of polymer-based magnetic nanocomposite for multi-pollutants removal from water,” Polymers (Basel)., vol. 13, no. 11, 2021, doi: 10.3390/polym13111742.
8. R. Ramadan, “Preparation, characterization and application of Ni-doped magnetite,” Appl. Phys. A Mater. Sci. Process., vol. 125, no. 9, pp. 1–8, 2019, doi: 10.1007/s00339-019-2887-z.
9. F. Almomani, R. Bhosale, M. Khraisheh, A. kumar, and T. Almomani, “Heavy metal ions removal from industrial wastewater using magnetic nanoparticles (MNP),” Appl. Surf. Sci., vol. 506, p. 144924, 2020, doi: 10.1016/j.apsusc.2019.144924.
10. K. Anbalagan, M. M. Kumar, J. S. Sudarsan, and S. Nithiyanantham, “Removal of heavy metal ions from industrial wastewater using magnetic nanoparticles,” J. Eng. Res., vol. 10, no. 4, pp. 59–71, 2022, doi: 10.36909/jer.6924.
11. M. F. Horst, M. Alvarez, and V. L. Lassalle, “Removal of heavy metals from wastewater using magnetic nanocomposites: Analysis of the experimental conditions,” Sep. Sci. Technol., vol. 51, no. 3, pp. 550–563, 2016, doi: 10.1080/01496395.2015.1086801.
12. A. Buccolieri et al., “Synthesis and Characterization of Mixed Iron-Manganese Oxide Nanoparticles and Their Application for Efficient Nickel Ion Removal from Aqueous Samples,” J. Anal. Methods Chem., vol. 2017, 2017, doi: 10.1155/2017/9476065.
13. Renu, M. Agarwal, and K. Singh, “Heavy metal removal from wastewater using various adsorbents: A review,” J. Water Reuse Desalin., vol. 7, no. 4, pp. 387–419, 2017, doi: 10.2166/wrd.2016.104.
14. M. A. Tahoon, S. M. Siddeeg, N. S. Alsaiari, W. Mnif, and F. Ben Rebah, “E ff ective Heavy Metals Removal from Water Using Nanomaterials : A Review,” pp. 1–24.
15. M. O. Usman, G. Aturagaba, M. Ntale, and G. W. Nyakairu, “A review of adsorption techniques for removal of phosphates from wastewater,” Water Sci. Technol., vol. 86, no. 12, pp. 3113–3132, 2022, doi: 10.2166/wst.2022.382.
16. Y. Tao, C. Zhang, T. Lü, and H. Zhao, “Removal of Pb(II) ions from wastewater by using polyethyleneimine-functionalized Fe3O4 magnetic nanoparticles,” Appl. Sci., vol. 10, no. 3, 2020, doi: 10.3390/app10030948.
17. S. M. Ansari et al., “Eco-Friendly Synthesis, Crystal Chemistry, and Magnetic Properties of Manganese-Substituted CoFe2O4Nanoparticles,” ACS Omega, vol. 5, no. 31, pp. 19315–19330, 2020, doi: 10.1021/acsomega.9b02492.
18. C. Nilsson, C. Nilsson, R. Lakshmanan, and G. Renman, “Efficacy of reactive mineral-based sorbents forphosphate , bacteria , nitrogen and TOC removal- Column experiment in recirculation batch mode Efficacy of reactive mineral-based sorbents for phosphate , bacteria , nitrogen and TOC removal e Column experime,” Water Res., no. May 2014, 2013, doi: 10.1016/j.watres.2013.05.056.
19. A. Singh, S. Chaudhary, and B. S. Dehiya, “Fast removal of heavy metals from water and soil samples using magnetic Fe 3 O 4 nanoparticles,” 2020.

20. M. Ul-Islam et al., “Current advancements of magnetic nanoparticles in adsorption and degradation of organic pollutants,” Environ. Sci. Pollut. Res., vol. 24, no. 14, pp. 12713–12722, 2017, doi: 10.1007/s11356-017-8765-3.
21. K. Singh, N. A. Renu, and M. Agarwal, “Methodologies for removal of heavy metal ions from wastewater: an overview,” Interdiscip. Environ. Rev., vol. 18, no. 2, p. 124, 2017, doi: 10.1504/ier.2017.10008828.
22. V. Dhiman and N. Kondal, “ZnO Nanoadsorbents: A potent material for removal of heavy metal ions from wastewater,” Colloids Interface Sci. Commun., vol. 41, no. October 2020, p. 100380, 2021, doi: 10.1016/j.colcom.2021.100380.
23. S. Singh Rathore, S. Tejasvi, and V. Gupta, “Elimination of Heavy Metal Ions from Industrial Wastewater: A Review,” Eur. Chem. Bull, vol. 2023, no. 1, pp. 1052–1065.
24. N. Ghosh, S. Das, G. Biswas, and P. K. Haldar, “Review on some metal oxide nanoparticles as effective adsorbent in wastewater treatment,” vol. 85, no. 12, pp. 3370–3395, 2022, doi: 10.2166/wst.2022.153.
25. G. H. Chala, “Review on Green Synthesis of Iron-Based Nanoparticles for Environmental Applications,” J. Chem. Rev, vol. 5, no. 1, pp. 1–14, 2023, [Online]. Available: https://doi.org/10.22034/JCR.2023.356745.1184
26. F. S. A. Khan et al., “Magnetic nanoparticles incorporation into different substrates for dyes and heavy metals removal—A Review,” Environ. Sci. Pollut. Res., vol. 27, no. 35, pp. 43526–43541, 2020, doi: 10.1007/s11356-020-10482-z.
27. R. Asadi, H. Abdollahi, M. Gharabaghi, and Z. Boroumand, “Effective removal of Zn (II) ions from aqueous solution by the magnetic MnFe2O4 and CoFe2O4 spinel ferrite nanoparticles with focuses on synthesis, characterization, adsorption, and desorption,” Adv. Powder Technol., vol. 31, no. 4, pp. 1480–1489, 2020, doi: 10.1016/j.apt.2020.01.028.
28. F. Asghar and A. Mushtaq, “The Future of Nanomaterial in Wastewater Treatment: A Review,” Int. J. Chem. Biochem. Sci., vol. 23, no. 1, pp. 150–157, 2023.
29. M. K. Bharti, S. Gupta, S. Chalia, I. Garg, P. Thakur, and A. Thakur, “Potential of Magnetic Nanoferrites in Removal of Heavy Metals from Contaminated Water: Mini Review,” J. Supercond. Nov. Magn., vol. 33, no. 12, pp. 3651–3665, 2020, doi: 10.1007/s10948-020-05657-1.
30. A. Predescu, E. Matei, A. Berbecaru, and R. Vidu, “Synthesis of Magnetic Nanoparticles for the removal of heavy metal ions from wastewaters,” Proc. 38th Annu. Congr. ARA, no. JULY 2014, pp. 37–42, 2015, doi: 10.14510/araproc.v0i0.1270.
31. S. M. Abdelbasir and A. E. Shalan, “An overview of nanomaterials for industrial wastewater treatment,” Korean J. Chem. Eng., vol. 36, no. 8, pp. 1209–1225, 2019, doi: 10.1007/s11814-019-0306-y.
32. T. D. Chaemiso, “Removal Methods of Heavy Metals from Laboratory Wastewater,” J. Nat. Sci. Res., vol. 9, no. 2, pp. 36–42, 2019, doi: 10.7176/jnsr/9-2-04.
33. G. N. Hlongwane, P. T. Sekoai, M. Meyyappan, and K. Moothi, “Simultaneous removal of pollutants from water using nanoparticles: A shift from single pollutant control to multiple pollutant control,” Sci. Total Environ., vol. 656, pp. 808–833, 2019, doi: 10.1016/j.scitotenv.2018.11.257.
34. Y. Zhang et al., “Ultrafast adsorption of heavy metal ions onto functionalized lignin-based hybrid magnetic nanoparticles,” Chem. Eng. J., vol. 372, no. April, pp. 82–91, 2019, doi: 10.1016/j.cej.2019.04.111.
35. R. Lakshmanan, C. Okoli, M. Boutonnet, S. Järås, and G. K. Rajarao, “Effect of magnetic iron

oxide nanoparticles in surface water treatment: Trace minerals and microbes," Bioresour. Technol., vol. 129, pp. 612–615, 2013, doi: 10.1016/j.biortech.2012.12.138.

36. F. Parvin, S. M. Tareq, and S. Y. Rikta, Application of Nanomaterials for the Removal of Heavy Metal From Wastewater. Elsevier Inc., 2019. doi: 10.1016/B978-0-12-813902-8.00008-3.

37. J. M. Arana Juve, F. M. S. Christensen, Y. Wang, and Z. Wei, "Electrodialysis for metal removal and recovery: A review," Chem. Eng. J., vol. 435, no. P2, p. 134857, 2022, doi: 10.1016/j.cej.2022.134857.

38. R. Vidu, E. Matei, A. M. Predescu, and B. Alhalaili, "Removal of Heavy Metals from Wastewaters :," pp. 1–37, 2020.

39. T. A. Aragaw, F. M. Bogale, and B. A. Aragaw, "Iron-based nanoparticles in wastewater treatment: A review on synthesis methods, applications, and removal mechanisms," J. Saudi Chem. Soc., vol. 25, no. 8, p. 101280, 2021, doi: 10.1016/j.jscs.2021.101280.

40. M. P. Ajith, E. Priyadarshini, and P. Rajamani, "Effective and selective removal of heavy metals from industrial effluents using sustainable Si–CD conjugate based column chromatography," Bioresour. Technol., vol. 314, p. 123786, 2020, doi: 10.1016/j.biortech.2020.123786.

41. V. K. Yadav, A. Amari, S. G. Wanale, H. Osman, and M. H. Fulekar, "Synthesis of Floral-Shaped Nanosilica from Coal Fly Ash and Its Application for the Remediation of Heavy Metals from Fly Ash Aqueous Solutions," Sustain., vol. 15, no. 3, 2023, doi: 10.3390/su15032612.

42. G. F. Stiufiuc and R. I. Stiufiuc, "Magnetic Nanoparticles: Synthesis, Characterization, and Their Use in Biomedical Field," Appl. Sci., vol. 14, no. 4, p. 1623, 2024, doi: 10.3390/app14041623.

43. D. Sahu, "REVIEW ARTICLE A Comprehensive Review on the Applications of ZnO Nanostructures Mechanisms," vol. 12, no. 67, pp. 33353–33360, 2021.

44. N. Akhlaghi and G. Najafpour-Darzi, "Manganese ferrite (MnFe2O4) Nanoparticles: From synthesis to application -A review," J. Ind. Eng. Chem., vol. 103, pp. 292–304, 2021, doi: 10.1016/j.jiec.2021.07.043.

45. A. Kaur and S. Sharma, "Removal of Heavy Metals from Waste Water by using Various Adsorbents- A Review," Indian J. Sci. Technol., vol. 10, no. 34, pp. 1–14, 2017, doi: 10.17485/ijst/2017/v10i34/117269.

46. S. V, "Applications of iron oxide nano composite in waste water treatment–dye decolourisation and anti–microbial activity," MOJ Drug Des. Dev. Ther., vol. 2, no. 5, pp. 178–184, 2018, doi: 10.15406/mojddt.2018.02.00058.

47. Y. Fei and Y. H. Hu, "Design, synthesis, and performance of adsorbents for heavy metal removal from wastewater: a review," J. Mater. Chem. A, vol. 10, no. 3, pp. 1047–1085, 2022, doi: 10.1039/d1ta06612a.

48. C. Sivaraman, S. Vijayalakshmi, E. Leonard, S. Sagadevan, and R. Jambulingam, "Current Developments in the Effective Removal of Environmental Pollutants through Photocatalytic Degradation Using Nanomaterials," Catalysts, vol. 12, no. 5, 2022, doi: 10.3390/catal12050544.

49. R. Kumar and J. Chawla, "Removal of Cadmium Ion from Water/Wastewater by Nano-metal Oxides: A Review," Water Qual. Expo. Heal., vol. 5, no. 4, pp. 215–226, 2014, doi: 10.1007/s12403-013-0100-8.

50. E. C. Nnadozie and P. A. Ajibade, "Multifunctional magnetic oxide nanoparticle (MNP) core-shell: Review of synthesis, structural studies and application for wastewater treatment," Molecules, vol. 25, no. 18, 2020, doi: 10.3390/molecules25184110.

51. S. Wadhawan, A. Jain, J. Nayyar, and S. K. Mehta, "Role of nanomaterials as adsorbents in

heavy metal ion removal from waste water: A review," J. Water Process Eng., vol. 33, no. October 2019, p. 101038, 2020, doi: 10.1016/j.jwpe.2019.101038.

52. N. Elboughdiri, "The use of natural zeolite to remove heavy metals Cu (II), Pb (II) and Cd (II), from industrial wastewater," Cogent Eng., vol. 7, no. 1, 2020, doi: 10.1080/23311916.2020.1782623.
53. Ž. Z. Tasić, G. D. Bogdanović, and M. M. Antonijević, "Application of natural zeolite in wastewater treatment: A review," J. Min. Metall. A Min., vol. 55, no. 1, pp. 67–79, 2019, doi: 10.5937/jmma1901067t.
54. T. P. Belova, "Adsorption of heavy metal ions (Cu2+, Ni2+, Co2+ and Fe2+) from aqueous solutions by natural zeolite," Heliyon, vol. 5, no. 9, p. e02320, 2019, doi: 10.1016/j.heliyon.2019.e02320.
55. Z. Cheng, A. L. K. Tan, Y. Tao, D. Shan, K. E. Ting, and X. J. Yin, "Synthesis and characterization of iron oxide nanoparticles and applications in the removal of heavy metals from industrial wastewater," Int. J. Photoenergy, vol. 2012, 2012, doi: 10.1155/2012/608298.
56. D. Stanicki, L. Vander Elst, R. N. Muller, and S. Laurent, "Synthesis and processing of magnetic nanoparticles," Curr. Opin. Chem. Eng., vol. 8, pp. 7–14, 2015, doi: 10.1016/j.coche.2015.01.003.
57. S. Nizamuddin et al., Iron Oxide Nanomaterials for the Removal of Heavy Metals and Dyes From Wastewater. Elsevier Inc., 2019. doi: 10.1016/B978-0-12-813926-4.00023-9.
58. A. Farhan et al., "Removal of Toxic Metals from Water by Nanocomposites through Advanced Remediation Processes and Photocatalytic Oxidation," Curr. Pollut. Reports, vol. 9, no. 3, pp. 338–358, 2023, doi: 10.1007/s40726-023-00253-y.
59. N. A. A. Qasem, R. H. Mohammed, and D. U. Lawal, "Removal of heavy metal ions from wastewater: a comprehensive and critical review," npj Clean Water, vol. 4, no. 1, 2021, doi: 10.1038/s41545-021-00127-0.
60. I. Elghamry, M. Gouda, and Y. S. S. Al-Fayiz, "Synthesis of Chemically Modified Acid-Functionalized Multiwall Carbon Nanotubes with Benzimidazole for Removal of Lead and Cadmium Ions from Wastewater," Polymers (Basel)., vol. 15, no. 6, 2023, doi: 10.3390/polym15061421.
61. A. M. Adam et al., "Pb (II), Cd (II) and Sn (II) Heavy Metals from Wastewater Using Novel Metal – Carbon-Based Composites," Crystals, vol. 11, no. Ii, p. 882, 2021.
62. M. R. Abukhadra, B. M. Bakry, A. Adlii, S. M. Yakout, and M. A. El-Zaidy, "Facile conversion of kaolinite into clay nanotubes (KNTs) of enhanced adsorption properties for toxic heavy metals (Zn2+, Cd2+, Pb2+, and Cr6+) from water," J. Hazard. Mater., vol. 374, no. April, pp. 296–308, 2019, doi: 10.1016/j.jhazmat.2019.04.047.
63. A. Dhillon and D. Kumar, New Generation Nano-Based Adsorbents for Water Purification. Elsevier Inc., 2019. doi: 10.1016/B978-0-12-813926-4.00036-7.
64. L. Jiao, H. Feng, and N. Chen, "Halloysite@polydopamine/ZIF-8 Nanocomposites for Efficient Removal of Heavy Metal Ions," J. Chem., vol. 2023, 2023, doi: 10.1155/2023/7182712.
65. C. I. Covaliu-Mierlă, O. Păunescu, and H. Iovu, "Recent Advances in Membranes Used for Nanofiltration to Remove Heavy Metals from Wastewater: A Review," Membranes (Basel)., vol. 13, no. 7, 2023, doi: 10.3390/membranes13070643.
66. I. H. Alsohaimi et al., "Chitosan Polymer Functionalized-Activated Carbon/Montmorillonite Composite for the Potential Removal of Lead Ions from Wastewater," Polymers (Basel)., vol. 15, no. 9, 2023, doi: 10.3390/polym15092188.

67. N. Meky, E. Salama, M. F. Soliman, S. G. Naeem, M. Ossman, and M. Elsayed, “Synthesis of Nano-silica Oxide for Heavy Metal Decontamination from Aqueous Solutions,” Water. Air. Soil Pollut., vol. 235, no. 2, pp. 1–30, 2024, doi: 10.1007/s11270-024-06944-6.

68. A. Jamshed, A. Iqbal, S. Ali, S. Ali, and . M., “A quick review on the applications of nanomaterials as adsorbents,” MOJ Ecol. Environ. Sci., vol. 8, no. 3, pp. 86–89, 2023, doi: 10.15406/mojes.2023.08.00278.

69. W. S. Chai et al., “A review on conventional and novel materials towards heavy metal adsorption in wastewater treatment application,” J. Clean. Prod., vol. 296, p. 126589, 2021, doi: 10.1016/j.jclepro.2021.126589.

70. D. T. K. Dung, T. H. Hai, L. H. Phuc, B. D. Long, L. K. Vinh, and P. N. Truc, “Preparation and characterization of magnetic nanoparticles with chitosan coating,” J. Phys. Conf. Ser., vol. 187, 2009, doi: 10.1088/1742-6596/187/1/012036.

71. Y. Wei, B. Han, X. Hu, and Y. Lin, “Procedia Engineering Synthesis of Fe 3 O 4 nanoparticles and their magnetic properties,” vol. 00, no. 2011, pp. 0–5, 2012, doi: 10.1016/j.proeng.2011.12.498.

72. R. Lakshmanan, Application of Magnetic nanoparticles and reactive filter materials for wastewater treatment, Doctoral thesis, no. December. 2013.

73. D. H. K. Reddy and Y. S. Yun, “Spinel ferrite magnetic adsorbents: Alternative future materials for water purification?,” Coord. Chem. Rev., vol. 315, pp. 90–111, 2016, doi: 10.1016/j.ccr.2016.01.012.

74. R. M R et al., “Carbonaceous MnFe2O4 nano-adsorbent: Synthesis, characterisation and investigations on chromium (VI) ions removal efficiency from aqueous solution,” Appl. Surf. Sci. Adv., vol. 16, no. January, p. 100434, 2023, doi: 10.1016/j.apsadv.2023.100434.

75. A. F. P. Allwin Mabes Raj et al., “Superparamagnetic Spinel-Ferrite Nano-Adsorbents Adapted for Hg2+, Dy3+, Tb3+ Removal/Recycling: Synthesis, Characterization, and Assessment of Toxicity,” Int. J. Mol. Sci., vol. 24, no. 12, 2023, doi: 10.3390/ijms241210072.

76. S. G. Muntean, L. Halip, M. A. Nistor, and C. Păcurariu, “Removal of Metal Ions via Adsorption Using Carbon Magnetic Nanocomposites: Optimization through Response Surface Methodology, Kinetic and Thermodynamic Studies,” Magnetochemistry, vol. 9, no. 7, 2023, doi: 10.3390/magnetochemistry9070163.

77. M. M. Arman, “Novel multiferroic nanoparticles Sm1−xHoxFeO3 as a heavy metal Cr6+ ion removal from water,” Appl. Phys. A Mater. Sci. Process., vol. 129, no. 6, 2023, doi: 10.1007/s00339-023-06666-2.

78. R. Lakshmanan and G. Kuttuva Rajarao, “Effective water content reduction in sewage wastewater sludge using magnetic nanoparticles,” Bioresour. Technol., vol. 153, pp. 333–339, 2014, doi: 10.1016/j.biortech.2013.12.003.

79. A. You, M. Be, and I. In, “Co-precipitation Synthesis of Magnetic Nanoparticles for,” no. December 2016, 2023.

80. J. Kong, K. Coolahan, and A. Mugweru, “Manganese based magnetic nanoparticles for heavy metal detection and environmental remediation,” Anal. Methods, vol. 5, no. 19, pp. 5128–5133, 2013, doi: 10.1039/c3ay40359a.

81. S. Shukla, R. Khan, and A. Daverey, “Environmental Technology & Innovation Synthesis and characterization of magnetic nanoparticles , and their applications in wastewater treatment : A review,” Environ. Technol. Innov., vol. 24, p. 101924, 2021, doi: 10.1016/j.eti.2021.101924.

82. C. Liosis, A. Papadopoulou, E. Karvelas, T. E. Karakasidis, and I. E. Sarris, “Heavy metal adsorption using magnetic nanoparticles for water purification: A critical review,” Materials (Basel)., vol. 14, no. 24, 2021, doi: 10.3390/ma14247500.
83. T. Naseem and T. Durrani, “Environmental Chemistry and Ecotoxicology The role of some important metal oxide nanoparticles for wastewater and antibacterial applications : A review,” Environ. Chem. Ecotoxicol., vol. 3, pp. 59–75, 2021, doi: 10.1016/j.enceco.2020.12.001.
84. C. Santhosh, E. Dhaneshvar, A. Bhatnagar, A. Malathi, J. Madhavan, and A. N. Grace, Iron Oxide Nanomaterials for Water Purification. Elsevier Inc., 2019. doi: 10.1016/B978-0-12-813926-4.00022-7.
85. R. Goyat, Y. Saharan, J. Singh, A. Umar, and S. Akbar, “Synthesis of Graphene-Based Nanocomposites for Environmental Remediation Applications: A Review,” Molecules, vol. 27, no. 19, pp. 1–34, 2022, doi: 10.3390/molecules27196433.
86. E. F. Joel and G. Lujanienė, “Progress in Graphene Oxide Hybrids for Environmental Applications,” Environ. - MDPI, vol. 9, no. 12, 2022, doi: 10.3390/environments9120153.
87. H. Chen, F. Liu, C. Cai, H. Wu, and L. Yang, “Removal of Hg2+ from desulfurization wastewater by tannin-immobilized graphene oxide,” Environ. Sci. Pollut. Res., vol. 29, no. 12, pp. 17964–17976, 2022, doi: 10.1007/s11356-021-16993-7.
88. P. G. Krishna et al., “Photocatalytic Activity Induced by Metal Nanoparticles Synthesized by Sustainable Approaches: A Comprehensive Review,” Front. Chem., vol. 10, no. September, pp. 1–21, 2022, doi: 10.3389/fchem.2022.917831.
89. C. Martinez-Boubeta and K. Simeonidis, Magnetic Nanoparticles for Water Purification. Elsevier Inc., 2019. doi: 10.1016/B978-0-12-813926-4.00026-4.
90. S. Mustapha et al., Application of TiO2 and ZnO nanoparticles immobilized on clay in wastewater treatment: a review, vol. 10, no. 1. Springer International Publishing, 2020. doi: 10.1007/s13201-019-1138-y.
91. J. Jiang et al., “We are IntechOpen , the world ’ s leading publisher of Open Access books Built by scientists , for scientists TOP 1 %,” Intech, vol. 34, no. 8, pp. 57–67, 2010, [Online]. Available: https://doi.org/10.1007/s12559-021-09926-6%0Ahttps://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics%0Ahttp://dx.doi.org/10.1016/j.compmedimag.2010.07.003
92. V. Anggraini, R. A. Putra, and T. A. Fadlly, “ Synthesis and Characterization of Manganese Ferrite (MnFe 2 O 4) Nanoparticles by Coprecipitation Method at Low Temperatures ,” Proc. 2nd Int. Conf. Sci. Technol. Mod. Soc. (ICSTMS 2020), vol. 576, no. Icstms 2020, pp. 118–122, 2021, doi: 10.2991/assehr.k.210909.028.
93. N. Bich, T. Tran, N. B. Duong, and N. L. Le, “Synthesis and Characterization of Magnetic Fe 3 O 4 / Zeolite NaA Nanocomposite for the Adsorption Removal of Methylene Blue Potential in Wastewater Treatment,” vol. 2021, 2021.
94. F. Y. Zhao, Y. L. Li, and L. H. Li, “Preparation and characterization of magnetite nanoparticles,” Appl. Mech. Mater., vol. 618, no. May, pp. 24–27, 2014, doi: 10.4028/www.scientific.net/AMM.618.24.
95. L. Thi Mong Thy et al., “Fabrication of manganese ferrite/graphene oxide nanocomposites for removal of nickel ions, methylene blue from water,” Chem. Phys., vol. 533, p. 110700, 2020, doi: 10.1016/j.chemphys.2020.110700.
96. A. Najafpoor et al., “Effect of magnetic nanoparticles and silver-loaded magnetic

nanoparticles on advanced wastewater treatment and disinfection," J. Mol. Liq., vol. 303, p. 112640, 2020, doi: 10.1016/j.molliq.2020.112640.
97. G. K. Salman, A. J. Bohan, and G. M. Jaed, "Use of Nano-Magnetic Material for Removal of Heavy Metals from Wastewater," Eng. Technol. J., vol. 35, no. 9, pp. 903–908, 2017, doi: 10.30684/etj.35.9a.6.
98. R. K. Gautam and M. C. Chattopadhyaya, "Functionalized Magnetic Nanoparticles: Adsorbents and Applications," Nanomater. Wastewater Remediat., pp. 139–159, 2016, doi: 10.1016/b978-0-12-804609-8.00007-8.
99. M. Mantovani, E. Collina, M. Lasagni, F. Marazzi, and V. Mezzanotte, "Production of microalgal-based carbon encapsulated iron nanoparticles (ME-nFe) to remove heavy metals in wastewater," Environ. Sci. Pollut. Res., vol. 30, no. 3, pp. 6730–6745, 2023, doi: 10.1007/s11356-022-22506-x.
100. M. Marganovici et al., "Hybrid Coordination Networks for Removal of Pollutants from Wastewater," Int. J. Mol. Sci., vol. 23, no. 20, 2022, doi: 10.3390/ijms232012611.
101. W. A. Review, A. A. Yaqoob, T. Parveen, and K. Umar, "Role of Nanomaterials in the Treatment of," 2020.
102. H. B. Desai, L. J. Hathiya, H. H. Joshi, and A. R. Tanna, "Synthesis and characterization of photocatalytic $MnFe_2O_4$ nanoparticles," Mater. Today Proc., vol. 21, pp. 1905–1910, 2020, doi: 10.1016/j.matpr.2020.01.248.
103. N. K. Balali-Mood M, K. S. M. (2021) Tahergorabi Z, F. P. 12:643972., and D. 10.3389/fphar.2021.643972, "No Title".
104. M. Zaim, A. Zaimee, and M. S. Sarjadi, "Heavy Metals Removal from Water by Efficient Adsorbents," 2021.
105. A. Mudhoo and M. Sillanpää, "Magnetic nanoadsorbents for micropollutant removal in real water treatment : a review," Environ. Chem. Lett., no. 0123456789, 2021, doi: 10.1007/s10311-021-01289-6.
106. H. Sadegh and G. A. M. Ali, "Potential Applications of Nanomaterials in Wastewater Treatment," no. June, pp. 51–61, 2018, doi: 10.4018/978-1-5225-5754-8.ch004.
107. R. Pirarath, P. Shivashanmugam, A. Syed, A. M. Elgorban, S. Anandan, and M. Ashokkumar, "Mercury removal from aqueous solution using petal-like MoS_2 nanosheets," Front. Environ. Sci. Eng., vol. 15, no. 1, pp. 1–10, 2021, doi: 10.1007/s11783-020-1307-0.