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Recent advances in the effective removal of hazardous pollutants from wastewater by using nanomaterials—A review

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Environmental nanotechnology has developed rapidly over the past few decades due to the fast advancement of nanotechnology and nanomaterials (NMs). Due to their nanoscale size, NMs are receiving immense attention in research and development worldwide. Their nano size has led to better catalysis, high reactivity, and high adsorption capacity. In wastewater treatment, nanotechnology has significant potential to improve the performance and efficiency of water decontamination; more effectively, it provides a sustainable way to keep water supplies safe. Numerous studies have found that removing harmful components from wastewater by employing nanoparticles in conjunction with various treatment methods is effective. The purpose of the current investigation is to conduct a review of the envisioned applications of various NMs in the treatment of wastewater. These NMs include carbonaceous NMs, metal-containing nanoparticles, and nanocomposites, all of which will be reviewed and highlighted in depth.

KEYWORDS

carbon nanotubes, graphene, nanocomposites, nanomaterials, wastewater

1 Introduction

Nowadays, the scarcity of water has become a large-scale problem for everybody. Clean water is a basic necessity for various purposes, including domestic, agricultural, industrial, and energy needs, particularly in developing countries where the population is rising (He et al., 2021; Yadav et al., 2023a). Every year a huge amount of fresh water is contaminated by various water pollutants, ultimately making the water unfit for drinking (Amari et al., 2023). The major pollutants of water are dyes, heavy metals, pesticides, microorganisms, hydrocarbons, and other toxic substances which challenge a potential threat to aquatic and living organisms (Nazari et al., 2021; Afolalu et al., 2022; Zhou et al., 2022a). Among heavy metals, the most common ones are mercury, arsenic, copper, nickel, zinc, *etc.*, In addition, it has been suggested that heavy metals like zinc and mercury can alter protein structure and result in cancer (Saeed and Shaker, 2008; Witkowska et al., 2021). Dyes discharged from the textile industries, *etc.*, lead to water pollution and disturb aquatic life as dyes prevent the penetration of sunlight to the deeper parts of the water bodies (Islam et al., 2023). Dyes polluted water may cause skin disorders and, in the long term, may cause cancer in living beings. Another major pollutant of water is pesticides (organophosphate, carbamate, organochlorine, pyrethroids, *etc.*) which come mainly from irrigation and agriculture (Ajiboye et al., 2022; Mishra et al., 2023). The agricultural fields introduced with pesticides leached with the rainwater and other water activities, ultimately reaching the freshwater bodies (Malla et al., 2021). These pesticides may accumulate in aquatic animals, which on consumption by humans, may lead to biomagnification (Ali et al., 2020; Gupta and Gupta, 2020). The consumption of pesticide-contaminated water in the long term may lead to numerous health-related disorders (Rajput et al., 2021; Tang et al., 2021). Pathogenic microorganisms are another major source of water pollution which mainly causes food and waterborne diseases (Kumar et al., 2021).

These effluents cause problems, including metal poisoning, irritations, and pathogenic infections in humans and animals (Briffa et al., 2020; Gaur et al., 2021). Good quality water is essential to sustain human wellbeing, livelihoods, and a healthy environment for sustainable development. As per the March 2020 WHO report, only 74% of the world's population (5.8 billion people) has access to safe water, while around two billion people use water contaminated with feces. In furtherance of this discussion, it appears that approximately 50% of the world's population will encounter water scarcity by 2025. In the past, the management of wastewater posed significant challenges. However, contemporary practices have evolved to include recycling, resulting in both wastewater treatment and a renewable energy source.

Currently, the majority of the investigations emphasize a particular method for the remediation of heavy metal ions, including electrocoagulation (EC), photocatalysis utilizing synthetic and natural adsorbents, the use of magnetic fields, advanced oxidation process (AOP), adsorption, membrane techniques, *etc.* (Singh et al., 2023a). Moreover, various nanomaterials (NMs) are utilized as nano-adsorbents, nano-catalysts, and nano-membranes for the treatment of wastewater effluents. Also, activated carbon nanotubes (CNTs), including both multi-walled and single-walled surfaces functionalized with decorated with zero-valent Ni NPs, are employed for the adsorption of heavy metals like (As, Cd, and Pb) from wastewater. Sagadevan et al. (2022) reported the titanium dioxide (TiO_2) based photocatalytic remediation of dyes and heavy metals from wastewater, while Aragaw and co-workers developed biomass-based adsorbents for the remediation of dyes from wastewater. Interestingly, Burk et al. (2020) reported Chitosan-coated gasifier biochar for the remediation of Cd (II) and Cu (II) from aqueous solutions (Aragaw and Bogale, 2021; Sagadevan et al., 2022).

Different treatment techniques are applied to remove toxic contaminants from wastewater, including chemical, biological, and ion exchange techniques, adsorption, and photocatalysis (Titchou et al., 2021; Ahmed et al., 2022; Yadav et al., 2023b). These treatment methods employed aim to enhance water quality; however, certain limitations are associated with some of these techniques. For instance, chemical methods often demand the use of a substantial quantity of chemicals, necessitate pH monitoring, result in sludge formation, and generate secondary pollutants due to excessive chemical usage (Bijekar et al., 2022). Also, adsorption techniques produce optional toxins. However, photocatalysis is a method that produces reactive chemical species that convert toxic pollutants into non-toxic byproducts and is sustainable, environmentally friendly, and clean (Huang et al., 2022). Photocatalysis is a rapidly developing technology attracting the attention of investigators due to its low cost and high efficiency in water decontamination compared to other methods (Khan, 2021).

Other promising techniques include membrane filtration and AOPs (Titchou et al., 2021). Membrane technology enables the effective separation of dyestuffs and dyeing auxiliaries, which concurrently mitigate the hydrolyzed color and biochemical oxygen demand/chemical oxygen demand of wastewater. These processes are typically used to treat effluent-reactive dye baths, which have the potential to reduce waste volume and recover salt at the same time. The utilization of the membrane filtration technique offers numerous advantages, including its expeditious nature and minimal spatial requirements (Asif and Zhang, 2021; Bhol et al., 2021).

AOPs are a newer, more powerful, and promising set of techniques developed and used to treat dye-contaminated effluents. The AOP technique has garnered considerable attention from the scientific community due to its user-friendly nature and its ability to generate substantially reduced residuals compared to conventional methodologies. AOPs exhibit superior performance compared to all currently available methodologies, albeit at a significantly higher cost (Ma et al., 2021a; Priyadarshini et al., 2022).

Chemical precipitation involves many disadvantages, like the production of a high amount of sludge, toxic by-products, time-consuming processes, and slow aggregation and settling of metal ions precipitate (Saleh et al., 2022). The cost of the regeneration process in the adsorption technique is high and may lead to adsorbent loss and its' effective performance. The frequent regeneration of ion-exchange resin in ion-exchange techniques leads to secondary pollution in the form of chemical reagents. Photocatalysis is mostly applicable for sludges and effluents, and the photo Fenton oxidation technique produces a large amount of iron-containing sludge (Al-Asheh and Aidan, 2020). Also, biological treatments are highly selective, toxic, sensitive to microorganisms, and require a large space for the bioreactors. Membrane processes (reverse osmosis, ultrafiltration, and nanofiltration) suffer from higher investment costs, maintenance, and operations. Membrane fouling high-pressure requirements for reverse osmosis are major disadvantages of this technique. AOPs outperform all existing ones but are much more expensive (Barakat, 2011; Qasem et al., 2021; Saleh et al., 2022).

Building upon the methodologies above, the field of nanoscale science is employed for the purposes of imaging, measuring, and modeling at its specific length scale. This utilization proves to be advantageous in the context of pollutant removal due to its recyclability, cost-effectiveness, and high efficiency. Recent research has indicated that there has been a notable increase in the industrial influence of nanotechnology applications (Puri et al., 2021).

Nanotechnology encompasses manipulating and studying matter at the atomic and molecular levels, focusing on dimensions approximately one billionth of a meter in scale (1×10^{-9} m = 1 nm) (Puri et al., 2021). A nanoparticle can generally be any size between 1 and 100 nm (Aniculaesei et al., 2019). Metallic nanoparticles (NPs) differ from bulk metals in their physical and chemical characteristics (e.g., lower melting points, higher specific surface areas, specific optical properties, specific mechanical strengths, and specific magnetizations), and these characteristics may be useful in a variety of industrial applications. Metals, metal oxides, polymers, and dendrimers are just a few of the many components that can be used to create these particles. Due to their distinctive features resulting from their small size and high surface area-to-volume ratio (SVR), synthetic NPs are engaged in numerous applications, including electronics, energy, medicine, and catalysis (Singh et al., 2022b). Several methods, such as chemical approaches (sol-gel, co-precipitation, *etc.*), physical vapor deposition (PVD), and material synthesis with template assistance, can be used to create synthetic NPs. Materials can suddenly display radically different properties when scaled down to the nanoscale from what they do at the macroscale (Saleh et al., 2022). For instance, opaque compounds can become transparent (like copper), inert substances can act as catalysts (like platinum), stable substances can catch fire (like aluminum), solids can convert into liquids at normal temperature (like gold), and insulators can act as conductors (like silicon) (Horikoshi and Serpone, 2013; Puri et al., 2021).

Due to their nanoscale size (~100 nm), NMs mechanically and electrically show a different behavior, and some of their optical and magnetic properties also differ from conventional materials (Alshammari et al., 2020; Modi et al., 2022). In the last past decades, many researchers are devoted to NMs preparation and also optimize them for information processing, machine learning (Jia et al., 2021), remote sensing (Altug et al., 2022; Bharadwaj et al., 2022), biomedical (Singh et al., 2020; Materón et al., 2021; Bagur et al., 2022), defense area, textile (Kabir et al., 2020), agriculture (Khan et al., 2023) and food industries (Modi et al., 2023b), environmental cleaning, etc (Baig et al., 2021). Nanotechnology is extensively being explored as a potential alternative in wastewater treatments like detoxication of water, desalination, *etc.*

The authors searched keywords, nanoparticles, nanomaterials, and wastewater treatment, on science direct.com by keeping the year limit "2018 to 2023" and found about 17,573 articles till 14 June 2023, out of which 3192 articles were published in 2023, 4775 in 2022, 3777 in 2021, 2601 in 2020, 1923 in 2019 and 1305 in 2018. Moreover, out of these 17,573 articles, 10,167 were research articles, 3,870 were review articles, 2,51 were book chapters, 269 were short communication, 98 were encyclopedias, 50 were conference abstracts, 30 were editorials, 10 were minireviews, 12 were case reports, 8 were discussion, data articles, and news were 5, correspondence was 2, practical guidelines and video articles were one each and rest 504 were others. The above investigation suggests that nanomaterials-based wastewater treatment is one of the latest topics among the scientific community around the whole globe, which is evidenced by the continuous and drastic increase in the articles every year from 2018 to 2023. Furthermore, the prevalence of research articles in this field suggests that further investigations are required to address the issue of water pollutants. So, the authors here tried to bridge the gap by providing the state-of-the-art in the field of nanomaterial-based wastewater treatment.

In this review, the authors have introduced the diverse categories of NMs and underscored their distinct properties that can be harnessed for addressing various pollutants in wastewater. The authors highlighted the significance of various NMs in the process of remediating dyes, heavy metals, pathogenic microorganisms, pesticides, and other substances. In this study, the authors have examined different categories of nanomaterials and their respective characteristics, which are employed in the process of sewer water reclamation.

2 Different classes of nanomaterials

Nanomaterials can be artificially synthesized in laboratory settings by manipulating different parameters to meet specific requirements. Additionally, NMs can also occur naturally as a result of various natural processes and activities. So, based on their origin, a nanomaterial could be classified into two categories: natural NMs, and laboratory-synthesized NMs (Das et al., 2020; Baig et al., 2021). Moreover, NMs could also be categorized based on their shapes, briefly discussed below. Figure 1 shows the major types of NMs based on their origin source, materials, and dimensions.

2.1 Natural nanomaterial

Natural NMs can be defined as substances that are formed through biogeochemical processes in a natural manner, without any contribution from human activities. These are intrinsic and present in natural bodies, e.g., viruses (capsid) and bone substances (Amin et al., 2014). Moreover, there are also formed by various natural activities, like clay, *etc.*

2.2 Laboratory-manufactured NMs

Laboratory-manufactured NMs refer to NMs that are artificially synthesized through the application of various methods. The entities above are further categorized into four distinct classes:

2.2.1 Carbon-based NMs

Carbon is present in these NMs, which are mainly of three types, i.e., which are hollow, ellipsoids (fullerenes), or tubes (CNTs). A team led by Sheron reported many applications of these NPs (single, double, and multi-walled nanotubes), like enhanced movies and coatings, many lighter materials, gadgets, and wastewater treatment. The utilization of graphene and carbon nanotubes (CNTs) in industries is attributed to their exceptional characteristics, including their high mechanical strength and lightweight nature (Fritea et al., 2021; Sheoran et al., 2022).

2.2.2 Metal-based NMs

This class comprises metal oxides (Al_2O_3, TiO_2) (Bousiakou et al., 2022), nano-sized gold, nano-sized silver (Bagur et al., 2022; Nadaf et al., 2022; Van Thuan et al., 2022), *etc.* Semiconductor

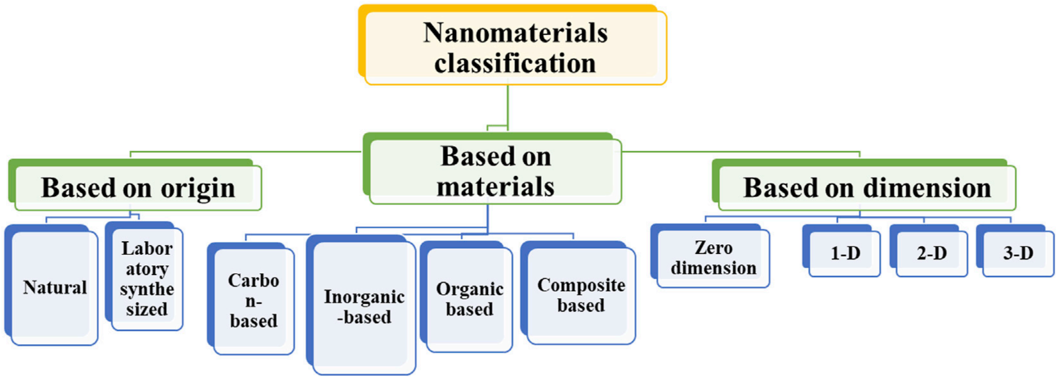

FIGURE 1
Classification of nanomaterials based on their origin source, materials, and dimensions.

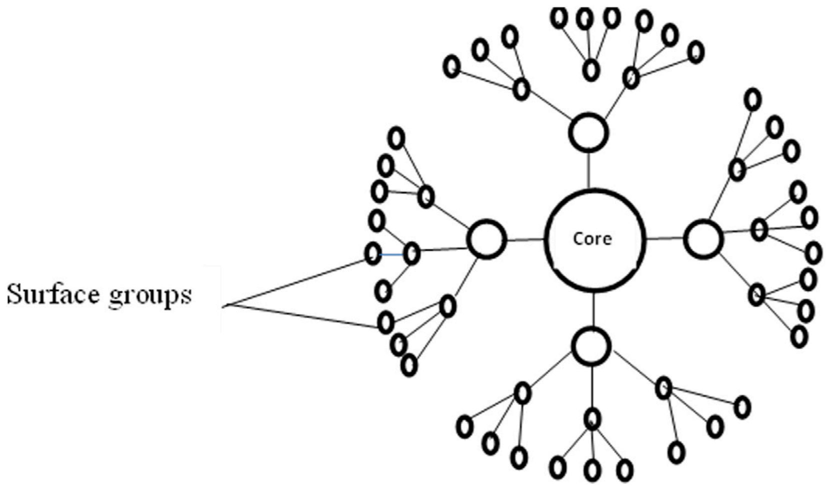

FIGURE 2
Representation of dendrimer.

quantum dots are crystals at the nanometer scale that possess distinctive photophysical characteristics, including optical properties that vary with size, high fluorescence quantum yields, and remarkable resistance to photobleaching (Villalva et al., 2021). The length of quantum dabs varies with their optical properties (Shah et al., 2015; Chopra et al., 2022).

2.2.3 Dendrimers

Dendrimer has a variety of chain closes on their surface, which is used to perform particular blended capacities. This property is necessary for catalysis. Similarly, 3-D dendrimers include inside depressions into which different atoms could be located, and they might be valuable for drug transportation, e.g., nano-sized polymers (Kaurav et al., 2023). A typical diagram of a dendrimer is shown in Figure 2.

2.2.4 Composites

These materials are used for combining NPs, which takes place with other NPs as well as large-sized materials. Mixing NMs with any metal, mass materials, and polymer can give rise to these composites (Gadore and Ahmaruzzaman, 2021; Levofloxacin et al., 2022; Zsirka et al., 2022).

2.3 Categorization of nanomaterial based on the dimension

The physical properties of some systems changed due to the spatial reduction of the nanoparticle structure. Based on dimensions, NMs (Figure 3) are classified as follows:

Zero dimension structures (0-D): System limited to three dimensions. All the dimensions are estimated within the nanoscale (less than 100 nm). It includes Ag/Au NPs, nanograins, nanoporous silicons, nanorings, and fullerene (Alam et al., 2021).

One dimension structures (1-D): System confined in two dimensions with mm long. It contains nanorods, nanotubes, and nanowires of metal oxides.

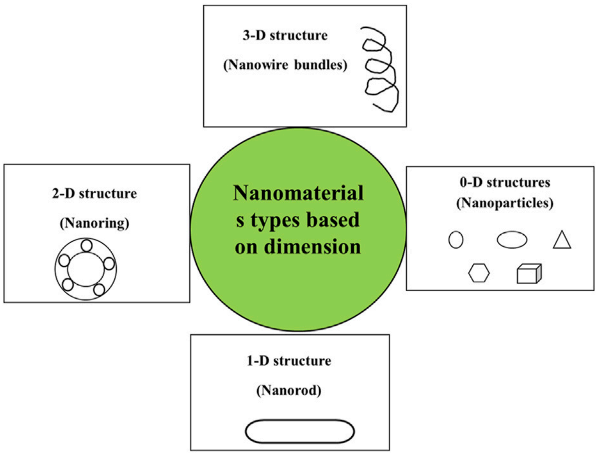

FIGURE 3
Various types of nanomaterials based on their dimension.

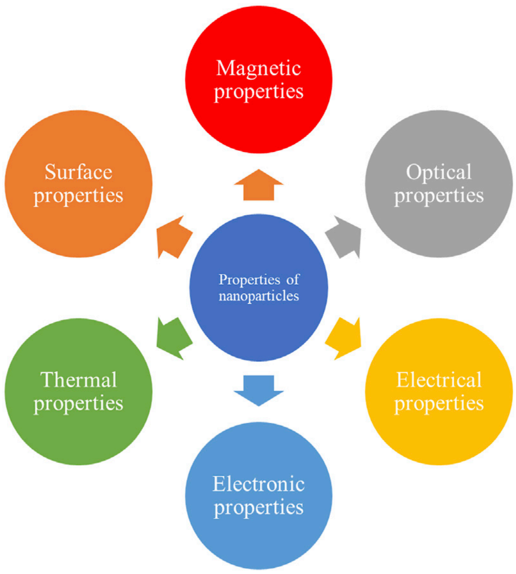

FIGURE 4
Various properties of nanoparticles.

Two-dimension structures (2-D): System limited to one dimension. It includes graphene, plate-like shapes, nanofilms, and nanolayers.

Three-dimension structures (3-D): The system is not confined in any dimension. It includes dispersions of NPs, nanowires, nanotubes multi-nanolayers, and bulk powders (Jagadeesh et al., 2017; Ba-Abbad et al., 2022; Yadav et al., 2023b).

3 Properties of nanoparticles

At nanoscale bulk, the properties of materials change drastically in comparison to their bulk counterparts. In addition to high SVR at the nanoscale (Jin and Higaki, 2021). Nanoparticles exhibit various additional characteristics, including alterations in magnetic, optical, electrical and electronic, thermal, and surface properties (Sajid and Płotka-Wasylka, 2020). All these properties are exploited in medicine, drug delivery, and environmental cleanup, which are discussed below in detail. Figure 4 shows the various types of properties that change at the nanoscale.

3.1 Magnetic properties

The higher surface area of NPs makes them unique and attractive. Magnetic NPs are utilized for cooling purposes, visualization, bioprocessing, higher cache memory materials, magnetic storage device, magnetic printing, *etc.* Giant magnetoresistance is a nanoscale multilayer containing ferromagnet (iron, cobalt, nickel) and non-attractive support materials (chromium, copper) which are used in data storage in memory (Shirsath and Shirivastava, 2015; Jefremovas et al., 2021).

3.2 Optical properties

The energies of orbitals (HOMO and LUMO) are mostly impacted by the nano size of the electronic structure (Sajid and Płotka-Wasylka, 2020). Due to these electrons, optical production and adsorption happen. The optical properties of many metals and semiconductors are changed extensively. The colloidal tension of Au NPs has dark red shading, which becomes dark yellow with an increase in particle size (Table 1) (Gnanamoorthy et al., 2020; Murthy et al., 2020; Zhu et al., 2020; Khan, 2021).

3.3 Electrical and electronic properties

The influence of size on electrical properties is a significant factor governed by scattering, electronic effects, and alterations in microstructure. When the material's dimension increases, it causes a reduction of defects, which results in a decrease in resistivity and an increase in conductivity. Decrease of dimension below a critical size, i.e., below De Broglie wavelength, results in a change of electronic structure, which takes place due to the widening of the bandgap and reduced electrical conductivity (Liu et al., 2021b).

3.4 Thermal properties

The exceptional properties of NPs include special heat, thermal conductivity (TC), and thermoelectricity (Almuallim et al., 2022; He et al., 2022). For instance, CNTs have a very strong TC, i.e., twice that of diamonds, and therefore act as great conductors of heat (Kumanek and Janas, 2019). Phonons are the primary means of determining thermal conductive properties and specific temperatures for nanotubes (Qian et al., 2021). Metal NPs have high TC compared to most liquids in solids, and the TC is greatly enhanced in nano liquids. For instance, at room temperature, the TC of Cu is approximately 700 folds that of H_2O and 3000 times that of

TABLE 1 Effect of size on the physical appearance and color of various nanoparticles.

S.No.	Nanoparticles	Size (nm)	Color shading	References
1	Au	2–5	Yellow	Hammami et al. (2021)
2		10–20	Red	Contini et al. (2020)
3		>20	Purple	Borse and Konwar (2020)
4	Ag	40	Blue	Vu et al. (2020), D'Ambrosio et al. (2022)
5		100	Yellow	Handayani et al. (2019)
6		Crystal moulded	Red	Dekker et al. (2021)
7	Cu	34.76 nm	light brownish	Parveen et al. (2016), Raina et al. (2020)
8		25 nm	Black brown	Maliki et al. (2022), Vasiliev et al. (2023)
9		40–60 nm	Saddle brown	Ramani et al. (2016), Waris et al. (2021)
10	Ti	40–60 nm	Black nanopowder	Andronic and Enesca (2020), Andronic et al. (2022)
11	TiO_2 nanopowder	10–30 nm	White nanopowder	Raut et al. (2016)
12	Fe	40–60 nm	Black nanopowder	Batool et al. (2021)
13	Fe_2O_3 nanopowder	20–40 nm	Red-brown nanopowder	Al-Musawi et al. (2023)
14	Zn	40–60 nm	Black nanopowder	Ringu et al. (2022)
15	ZnO	10–30 nm	white ~ light yellow nanopowder	Sadak and Bakry (2020)
16	Mo	40–60 nm	Black nanopowder	Gu et al. (2018)
17	MoO_3 NPs	<100 nm	Light blue	Kaur et al. (2021), Sharma et al. (2022)

TABLE 2 Thermal conductivity of nanomaterials.

Nanomaterials	Thermal conductivity [W/m·k]	References
Nano-Cu	401	Abdul Rahim et al. (2017)
Nano-MgO	50.1	Ibrahim et al. (2022)
Nano-TiO_2	300–770	Ibrahim et al. (2022)

motor oil (Czaplicka et al., 2021; Zhou et al., 2022b). Aluminum oxide exhibits a higher TC when compared to water. Hence, it can be inferred that nanofluids exhibit a higher thermal conductivity than fluids that incorporate fine particles and conventional heat transfer fluids (Coccia et al., 2021). This phenomenon can be attributed to the positive correlation between surface area and heat transfer efficiency. Table-2 shows the TC of a few NMs.

3.5 Surface properties

Surface properties like surface energy, particle-particle interaction, and surface modification primarily determine the agglomeration state of the particles and, therefore, their effective size, especially under physiological conditions (Coccia et al., 2021; Urian et al., 2021). Thus, the biological identity of a nanomaterial is clearly influenced by differentiating surface properties. This behavior is particularly relevant for biomedical applications. NPs possess quantum properties due to their very high ratio of atoms on the surface in comparison to the interior of the particle. Consequently, NPs are subject to distinct laws that differ from those governing larger matters. For example, gravitational forces do not exert influence on them; rather, they are governed by forces such as Van der Waals interactions (Bantz et al., 2014).

Activated carbons do not fulfill the criteria established in the different definitions of NMs provided by the existing regulations. Some of the Regulations and Scientific guides that have been evaluated are:

European Commission Recommendation for the definition of Nanomaterials, 2011/696/EU. It was intended to be applied as an overarching framework with regard to other EU regulations (Benko, 2017).

NB: Activated Carbons have been cited by ECHA as an example of a substance that might be interpreted as a nanomaterial based on the VSSA criteria. According to the literature, activated carbons possess a high surface area, although they do not fall under the category of NMs. Rather, they exhibit highly porous structures (Heidarinejad et al., 2020; Rao et al., 2021).

4 Positive and negative aspects of nanotechnology and nanomaterials

4.1 Positive aspects of nanotechnology and nanomaterials

The majority of the technological goods we use now are made with nanotechnology. Nobody could have expected that a gadget

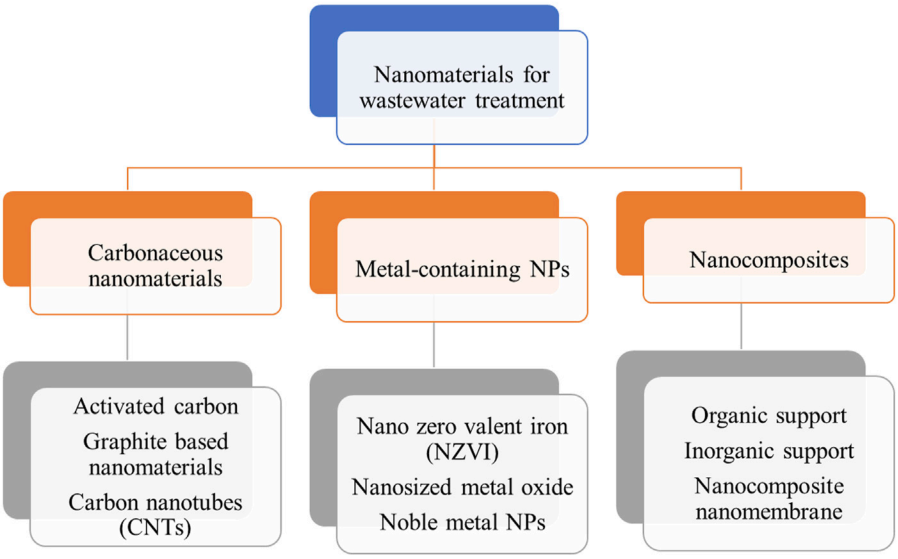

FIGURE 5
Schematic diagram of various nanomaterials for wastewater Treatment.

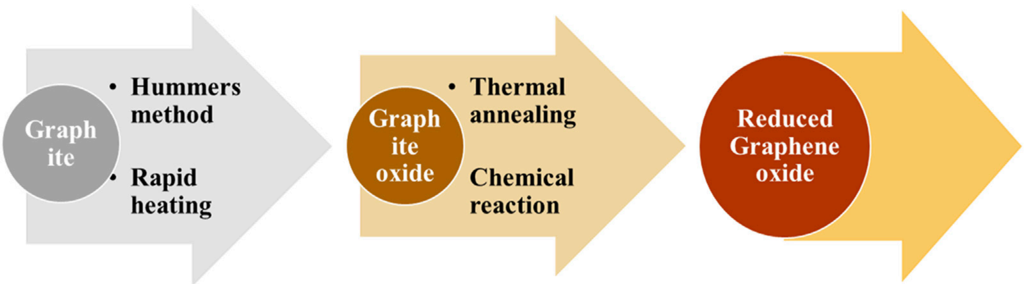

FIGURE 6
Block diagram for the preparation of GO and rGO.

with thousands of memory cells would be that small. The complex circuitry of the chip has achieved its objective by making it portable, enabling users to carry any electronic device from one location to another. We no longer need supercomputers to do easy mathematical computations. Instead, we can do even more complicated calculations on smartphones (Thiruvengadam et al., 2018; Nile et al., 2020).

Nanotechnology has substantially enhanced medical research, thereby providing a valuable contribution to the healthcare sector (Anjum et al., 2021). The illness can now be easily detected, and treatment options are widely available. The medical profession has invented several drugs and medical equipment, such as nanorobots, to treat incurable medical conditions such as cancer by completely utilizing nanotechnology (Haleem et al., 2023). As a result, nanotechnology is advantageous to the healthcare sector. Nanotechnology is often used to detect and treat hidden disorders. Any critically ill person can now be easily accessed and diagnosed using a range of technologies that were formerly huge and immovable (Curvino et al., 2021).

4.1.1 Benefits of production

Modern manufacturing requires nanoproducts such as nanotubes, NPs, nanobatteries, and so on that are more resilient, powerful, and lightweight than comparable products created without the use of nanotechnology. Hence, due to nanotechnology, the environment for manufacturing has changed and has become much better for them (Hansen et al., 2020).

4.1.2 Energy creation

Nanotechnology has considerably aided in the field of energy generation. Batteries, cells, and various other energy-efficient storage devices have become commonplace. All of these have been demonstrated to be energy-saving devices that have enhanced people's lives (Pomerantseva et al., 2019; Manickam et al., 2021).

TABLE 3 Applications of graphene, GO, rGO, and modified graphene as adsorbents for contaminants removal from wastewater.

S.No.	Adsorbents	Adsorption capacity (mg/g)	Contaminants	References
1	Graphene	35.6	Fluoride	Xu and Wang (2017)
2		89.37	Phosphate	Vasudevan and Lakshmi (2012)
3	Graphene-polypyrrole	-	Perchlorate	Zhang et al. (2011b)
4	Graphene-CNT	81.97	Methylene blue (MB)	Ai and Jiang (2012)
5	Graphene Oxide (GO)	108.342, 80.775, 71.378	Au(III), Pd(II), Pt (IV), Zn(II)	Liu et al. (2013), Abdullah et al. (2019)
6		1.222 (μg/g)	Cr(VI)	Mondal and Chakraborty (2020)
7		-	Organic pollutants	Sun et al. (2012)
8		190	Humic acid	Hartono et al. (2009)
9		313–398	Antibiotics	Gao et al. (2012)
10		16.83, 63.69	Methyl orange, Basic red 12	Robati et al. (2016)
11		5.496 (mmol/g)	Methyl green	Sharma and Das (2013)
12		149.4	Endocrine-disrupting chemicals (17β-Estradiol)	Zhao et al. (2021)
13		Enrofloxacin (ENF): 45.035, Rhodamine B (RhB): 107.230	ENF and RhB	Yang et al. (2022)
14	(Ethylenediaminetetraacetic acid) EDTA-GO	479 ± 46	Pb(II)	Madadrang et al. (2012)
15	GO- Fe_3O_4	MB: 37.5–108 (at 25 °C and 9 pH)	MB	Shi et al. (2022)
16	GO		Pesticides: carbaryl, catechol, and fluridone	Wang et al. (2021)
17	GO- $MnFe_2O_4$	673, 146, 207	Pb(II), As(III), As(V)	Kumar et al. (2014)
18	GO–$ZrO(OH)_2$	95.15, 84.89	As(III), As(V)	Luo et al. (2013)
19	RGO-Hydrogels	7.85, 29.44	MB, Rhodamine B	Tiwari et al. (2013)
20	RGO/Poly (acrylamide)	1000	Pb(II)	Rajabi et al. (2020)
21	RGO-PVP	1689	Cu(II)	Yang et al. (2020)
22	RGO-polyurethane	-	Cu(II)	Zhu et al. (2016)
23	Polyethylenimine modified-GO hydrogel		Pb (II)-602, Hg (II)-374 and Cd (II)-181	Arshad et al. (2019)
24	$MnFe_2O_4$/rGO magnetic NPs	105 (pH 7.5)	MB dye	Adel et al. (2020)
25	$MnFe_2O_4$/reduced GO (MrGO)	Malachite green dye (MG): 156, and MB: 105	MG and MB	Adel et al. (2021)
26	GO/Fe_3O_4/chitosan	MB	Maximum monolayer capacity: 30.10 mg g−1	Tran et al. (2017)
27	rGO/$ZnCo_2O_4$		Antimicrobial, electrochemical and photocatalytic effect	Gnanamoorthy et al. (2021)
28	rGO/$CuNiO_2$		MB	Gnanamoorthy et al. (2022)
29	rGO/nZVI		Doxycycline	Abdelfatah et al. (2022)

Due to the significant advancements facilitated by nanotechnology have greatly enhanced the potential to effectively address diseases. A wide array of tools and instruments have been employed in managing and mitigating diverse chronic diseases and ailments that currently lack a definitive cure. The diagnosis of the illness can be facilitated through the utilization of nanotechnology. After a diagnosis, treating the medical condition and helping the patient recover quickly is much easier.

TABLE 4 Application of CNTs for the removal of heavy metal ions from wastewater.

Adsorbent	Pollutants	Adsorption capacity (mg/g)	References
SWCNTs	Zn(II)	11.23	Lu and Chiu (2006)
SWCNTs/NaOCl		43.66	
MWCNTs		10.21	
MWCNTs/NaOCl		32.68	
As-grown CNTs	Cd(II)	1.1	Li et al. (2006)
CNTs/H_2O_2		2.6	
Ag-MWCNTs		16.95	
CNTs/MnO_2	Pb(II) -	78.74	Zhao et al. (2009)
SWCNTs	Ni(II)	9.22	Lu and Liu (2006)
SWCNTs/NaOCl		47.85	
MWCNTs		7.53	
MWCNTs/NaOCl		38.46	
MWCNTs	As(V)	Adsorption capacity 200 mg/g	Egbosiuba et al. (2020)
	Mn(VII)	Adsorption capacity 198 mg/g	
MWCNTs-OCH_2CO_2H	As(V)	250 mg/g	
	Mn(VII)	298 mg/g	
MWCNTs (5–15 nm diameter)	Pb(II)	215.38 ± 0.03 mg/g	Egbosiuba et al. (2021)
	Ni(II)	230.78 ± 0.01 mg/g	
MWCNTs (16–25 nm diameter)	Pb(II)	201.35 ± 0.02 mg/g	
	Ni(II)	206.40 ± 0.02 mg/g	
MWCNTs	Cu(II)	364.66 mg/g	Egbosiuba and Abdulkareem (2021)
	Zn(II)	347.01 mg/g	
Oxidized-MWCNTs	Cu(II)	416.47 mg/g 411.88 mg/g	
	Zn(II)	411.88 mg/g	
Pure-MWCNTs	Fe (II), Mn (II), Zn (II)		Aliyu et al. (2023)
Ag-MWCNTs	Fe (II), Mn (II), Zn (II)		
CNTs, Treated CNTs and PN@TR-CNTs	Cd(II), Cu(II), Fe(II), Ni(II) and Pb(II)		Abdulkareem et al. (2023)
MWCNTs-KOH	Pb(II)	68.4% ± 5.0%	Egbosiuba et al. (2022)
	As(V)	65.5% ± 4.2%	
	Cd(II)	50.7% ± 3.4%	
MWCNTs-KOH@NiNPs	Pb(II)	91.2% ± 8.7%	
	As(V)	88.5% ± 6.5%	
	Cd(II)	80.6% ± 5.8%	

4.2 Negative aspects of nanotechnology and nanomaterials

4.2.1 Negative environmental impact

The progression of nanotechnology has led to a rise in pollution, primarily related to the generation of NPs while manufacturing diverse pharmaceuticals, atomic weaponry, and other commodities. As a consequence, nanotechnology has a substantial environmental impact. In addition to human beings, the animals inhabiting these areas have been affected by various diseases (Del Prado-Audelo et al., 2021; Phillips, 2021).

4.2.2 A rise in unemployment is possible

The advancement of science and technology has significantly reduced the demand for human labour. As a consequence, a

TABLE 5 Remediation of heavy metals and other pollutants using nano-sized zero-valent iron from wastewater.

Adsorbents	Contaminants	References
Nano-sized zero-valent iron	Cd, Cr	Boparai et al. (2011), Yu et al. (2014)
	U(VI)	Crane et al. (2011)
	Cu(II)	Li et al. (2014)
	Pb (II), Cd (II)	Yadav and Fulekar (2018)
	As (0), As(III) and As(V)	Ramos et al. (2009)
	Nitrate	Ryu et al. (2011)
	Azo dye, Methyl orange	Fan et al. (2009)
	Antibiotics	Fang et al. (2011)
	Decabrominated diphenyl ether	Shih and Tai (2010)
	Pb (II), Cd(II), Cu (II)	Tarekegn et al. (2021b)
	V^{5+}	Liu et al. (2022)
	Direct Red-31 (DR-31) and Direct Brown-2 (DB-2)	Pourabadeh et al. (2020)
	Furfural	Rashtbari et al. (2022)
	MB	Tarekegn et al. (2021a)
Sulfidated nZVI with a chelator	Acid Red 73 (AR 73)	Zhang et al. (2019)
Hydrotalcite-Supported nZVI	MB	Fan et al. (2023)
nZVI-Cu bimetals	Nitrate	Zhang et al. (2022)
Solid carbon source/nZVI	Nitrate	Sun et al. (2021)
nZVI	Cd(II), Ni(II), Pb(II), Hg(II), Cu(II) and Cr(VI)	Feng et al. (2022)

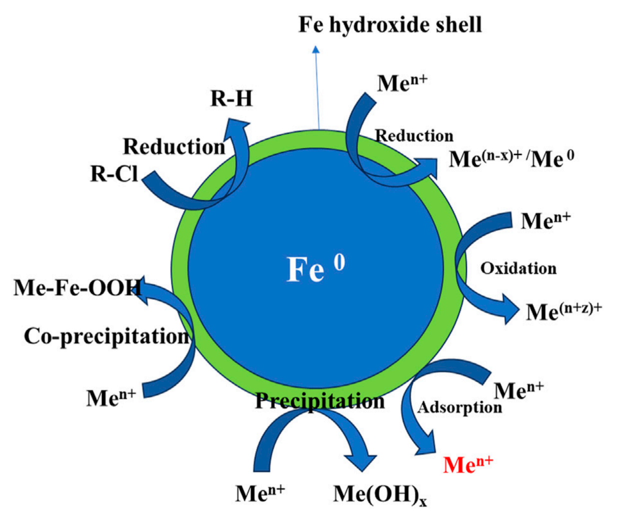

FIGURE 7
Core-shell structure of nZVI depicting various mechanisms for the removal of metals and chlorinated compounds reproduced from O'Carroll et al. (2013).

significant number of individuals have relinquished their employment positions due to technological advancements replacing their roles. Engineering nanotechnology has led to enhanced machine functionalities and the reduction of labour-intensive positions, particularly in the field of chemistry (Ma et al., 2021b; Pokrajac et al., 2021).

4.2.3 Accessible dangerous weapons

Numerous weapons generated through nanotechnology exhibit deleterious properties and are vulnerable to misuse by humans. In today's world, countries employ a diverse array of armaments to enhance their military capabilities. In the contemporary era, a nation possesses the capacity to construct and utilize weaponry such as atomic bombs with relative ease, thereby enabling the destruction of its adversaries (Khan et al., 2019).

4.2.4 Expensiveness

Nanotechnology, while advantageous in the fields of medicine, engineering, and material sciences, incurs significant expenses due to elevated operating and raw material expenditures. Consequently, the acquisition of the technology generally proves to be prohibitively costly for individuals of average means (Ray and Bandyopadhyay, 2021).

4.2.5 Nanotoxicity associated with the nanoparticles

The entry of these NPs into the ecosystem can occur through various pathways such as air, water, and soil, potentially resulting in nano-toxicity. Furthermore, as a result of its small size, it has the potential to permeate the dermal pores of individuals and contribute to the occurrence of metal-associated diseases, such as those

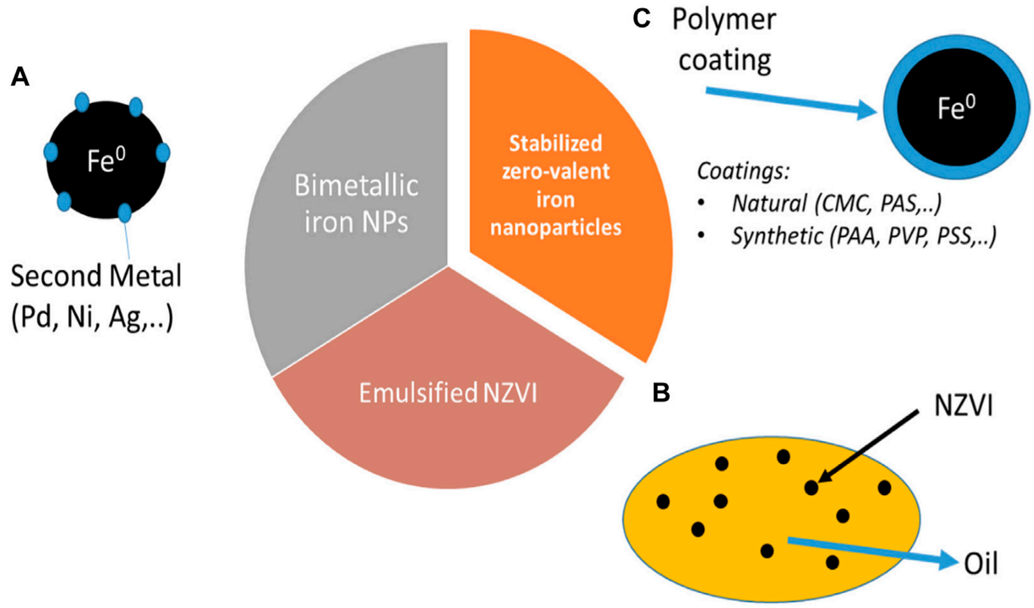

FIGURE 8
Main nZVI groups used for environmental applications: **(A)** Bimetallic iron nanoparticles, **(B)** emulsified nZVI, and **(C)** stabilized nZVI adapted from Galdames et al. (2020).

associated with the utilization of zinc oxide (ZnO), titanium dioxide (TiO_2), and silver (Ag) in cosmetic and toothpaste products.

5 Applications of nanomaterials for wastewater treatment

Numerous contaminants in water waste are detected and removed by applying nanotechnology. Non-biodegradable heavy metals are very toxic and adversely affect the lives of animals, plants, and living organisms, which become a scary situation for the environment (Yadav et al., 2023b). This problem can be solved by using NPs in the form of metal oxides (Ti, Zn), membranes (ceramic, polymer, nanowire, polymer), CNTs, nanopowder, *etc.* Water quality can be improved by different methods available like photocatalysis, electrochemical oxidation, nanofiltration, and adsorption methods which utilize the above-said materials (Yadav et al., 2022a).

NPs play a different role in the removal of toxic ions through adsorption, and chemical or photochemical oxidation processes, which is necessary for contaminants' destruction (Isawi, 2020). Another important role of NMs is as functional materials such as carbonaceous NMs, nano adsorbents, nanofibers, nano clays (Biswas et al., 2020), zeolites (Murukutti and Jena, 2022), and dendrites. Various NMs are used for the treatment and purification of water (Figure 5) (Singh et al., 2022a).

5.1 Carbonaceous nanomaterials for wastewater treatment

In the current decade, dyes and heavy metals are removed by using various kinds of carbon-containing NMs due to their non-toxicity, structure, abundance, high surface area, porosity, and good sorption limits (Fritea et al., 2021; Gacem et al., 2022).

5.1.1 Activated carbon

Agricultural wastes coal, wood, and coconut shells are used as carbon-based precursors for the synthesis of activated carbon, which possesses high porosity and high surface area and is used as sorbents (Igwegbe et al., 2021; Yilmaz et al., 2022). Machado and their group used coconut tree sawdust and prepared activated carbon, which was then utilized for Cr (VI) remediation. Arcibar-Orozco et al. studied the phosphate effect in forced hydrolysis of ferric chloride on modified granular activated carbon (Saleem et al., 2019; Rajendran et al., 2021).

5.1.2 Graphene-based nanomaterials

Graphene forms a graphite structure in a two-dimensional honeycomb pattern that shows tremendous thermal and electrical conductivity. Graphene oxide (GO), which consists of hydroxyl, epoxy, and carbonyl groups, is obtained by monolayer graphene with oxidative form. Zhu et al. (2016) elucidated five potential interactions, namely, hydrogen bonding, π-π bonding, the hydrophobic effect, covalent bonding, and electrostatic interactions, that contribute to the process of adsorption (Zhu et al., 2016). Xu and Wang (2017) reported graphene-based material for wastewater treatment, which has a large surface area and oxygen in large quantities. Avouris and Dimitrakopoulos compared reduced graphene oxide (rGO) and graphene and found that functional group modification of rGO improved its' imperfectness and conduction (Xu and Wang, 2017). The preparation of both of these oxides is shown in Figure 6.

For the remediation of contaminants such as heavy metals of lead, zinc, copper, cadmium, mercury, and arsenic, graphene-based materials act as good adsorbents. The utilization of two effective

TABLE 6 Application of metal oxides-based nanoparticles for the remediation of wastewater pollutants.

S. No.	Adsorbents	Target contaminant	References
1	Goethite (α-FeOOH)	Cu(II)	Grossl et al. (1994), Mohapatra et al. (2010)
2	Hematite (α- Fe_2O_3)	Pb(II), Cd(II), Cu(II), Zn(II)	Shipley et al. (2013)
3	Maghemite (γ-Fe_2O_3)	Cr(VI), Cu(II), Ni(II)	Jing et al. (2006)
4	Magnetite (Fe_3O_4)	Se(IV)	Wei et al. (2011)
5	Hydrous ferric oxide (HFO)	Fluoride	Nur et al. (2014)
6	Al_2O_3	Pb(II), Cd(II), Cr(III), Co(II), Ni(II), Mn(II)	Afkhami et al. (2010)
7	ZnO	MB dye	Modi et al. (2023b)
8	ZnO	Ampicillin (antibiotic) and MB	Soltani et al. (2023)
9	ZnO	Zn(II), Cd(II), Hg(II)	Sheela et al. (2012)
10	Amorphous IONPs from incense sticks ash (ISA)	Congo red (CR)	Yadav et al. (2022a)
11	Mesoporous and floral shaped SiO_2 from CFA	Al, Pb, Cd, Cu, Cr, Ni, Co, Zn, Mn	Yadav et al. (2023b)
12	$CaCO_3$ (vaterite and calcite) from ISA	Methyl red dye	Yadav et al. (2022b)
13	TiO_2	Antimicrobial activity and MB removal	Aravind et al. (2021)
14	Bismuth oxide doped MgO	Indigo Carmine (IR)	Adam et al. (2022)
15	MgO-nanosheets	Reactive orange and reactive yellow	Dalvand et al. (2020)
16	Fe_3O_4 NPs (leaf extract of Cola nitida)	MB (530.406 mg/g) within 1 h	Alex Mbachu et al. (2023)
		Methyl orange (527.835 mg/g) within 1 h	
17	ZnO	MB: 64%–83%	Modi et al. (2023a)
		COD: 15%–53%	
		TOC:31%–74.12%	
	ZnO-W	MB: 20%–88.21%	
		COD: 25%–85.2%	
		TOC:46.5%–92.04%	
	ZnO-Sb	MB:21%–91%	
		COD: 27%–88.5%	
		TOC: 48%–95.34%	

methods, namely, surface modification, and hybridization, enhances the working efficiency and reusing capacity of these materials. These substances have proven to be highly effective in the process of water decontamination, efficiently eliminating a wide range of pollutants (Mehdizadeh et al., 2014; Yadav and Fulekar, 2018; Irannajad and Kamran Haghighi, 2021). Although, their high cost is one of the main limitations in their application for environmental protection. Contaminants (metals and dyes) are removed by these materials due to their adsorption capacity, and for organic pollutants, removal by graphene, GO, rGO, and modified graphene is utilized, as shown in Table 3.

5.1.3 Carbon nanotubes (CNTs)

Carbon nanotubes possess new exceptional structural, mechanical, electrical, and magnetic properties, which make them unique in nanoelectronics. CNTs are mainly composed of carbon and exhibit stability, low reactivity and act as strong antioxidants. Their primary examples are CNTs, nanodiamonds, Fullerenes/Buckyballs (C60, C20, C70), and nanowires. These occur in different varieties like ellipsoids, nanowires, buckyballs, tubes (nanotubes), and nanodiamonds (Lin et al., 2018; Balarak et al., 2021). CNTs are used for wastewater management due to their easy conversion, large adsorption capacity, cylindrical hollow structure, high ratio aspect, and hydrophobic wall surfaces (Gacem et al., 2022). A team led by Rajabi et al. (2017) highlighted the utilization of multi-walled CNTs for the aqueous removal of methylene-based dyes like methylene red and MB. Table 4 displays the comparative results of CNTs and their adsorption capacity by which heavy metal ions get removed.

5.2 Metal-containing nanoparticles

Several nano-sized metals and metal oxides are used widely for the remediation of pollutants from water waste due to their higher

TABLE 7 Application of various nanoparticles for the removal of water contaminants.

Polymeric host	Nanoparticles	Removal	References
Polymeric anion exchangers	Hydrated ferric oxide	Phosphate 100 to <5 ppb	Zhao et al. (2011), Uwamungu et al. (2022)
Polymeric anion exchangers		As(III) removed from (100 to <10 ppb); As(V) (100 to <0.5 ppb)	Katsoyiannis and Zouboulis (2002), DeMarco et al. (2003), Cumbal and SenGupta (2005), Zhang et al. (2011a)
Polyacrylamide		211.4 mg for Pb (II), 155.0 mg for Hg(II), 147.2 mg for Cd(II)	Manju et al. (2002), Wu et al. (2020)
Polymeric ion exchanger		As (60 to<10 ppb)	Vatutsina et al. (2007)
Polystyrene anion exchanger		Phosphate	Lu et al. (2012)
Alginates	Iron oxides	As (50 to <10 ppb) MB, methyl orange (MO)	Zouboulis and Katsoyiannis (2002), Rocher et al. (2008), Sutirman et al. (2021)
Cyclodextrin		Cu(II)	Li et al. (2019)
Cellulose	Iron oxyhydroxide	As(III) (99.6 mg), As(V) (33.2 mg)	Guo and Chen (2005), Guillem-Navajas et al. (2022), Zanata et al. (2022)
Polymeric cation exchanger	Zirconium phosphate	Pb(II), Cd(II), Zn(II)	Zhang et al. (2008)
Halloysite/alginate	Hydrous ferric oxide	Pb(II)	Chiew et al. (2014)
Polypyrrole/montmorillonite	Titanium (IV)phosphate	Cr(VI)	Baig et al. (2015)
Polystyrene cation exchanger	Hydrous manganese dioxide	Tl(I)	Pan et al. (2014a)
-	ZnO NPs	Ampicillin (97%)	Soltani et al. (2023)
-	ZnO NPs	MB dye	Soltani et al. (2023)
Polyaniline	Ti(IV) arsenophosphate	Pb(II)	Baig et al. (2015)
Hybrid anion exchanger	Hydrated ferric oxide	Phosphate	Blaney et al. (2007)
Polystyrene	Hydrous manganese dioxide	Pb(II)	Jiang et al. (2011), Zhu and Li (2015)
	nZVI, Li/Al-based double-layered hydroxides	Nitrate reduction, Fluorides	Cai et al. (2016)
Polymeric cation exchanger	Polyethyleneimine (PEI) Nanoclusters	Cu(II)	Chen et al. (2010)
Cellulose	Au	Dyes	Wei et al. (2015)
Chitin- and chitosan	Ag, ZnS, Cu	Au(II), Al(III), Cd(II), Cu(II), bilirubin, organic dye, etc	Bhatnagar and Sillanpää (2009), Liu et al. (2012a), Jaiswal et al. (2012), Mansur et al. (2014)
-	ZnO NPs	MB dye (76%–95%)	Modi et al. (2023b)
-	Silica NPs	Al (II), Pb (II), Cd (II), Cu (II), Cr, Ni (II), Co (II), Zn (II), Mn (II) (40%–90%)	Yadav et al. (2023b)
-	Iron oxide NPs (IONPs) from coal fly ash	Al (II), Pb (II), Cd (II), Cu (II), Cr, Ni (II), Co (II), Zn (II), Mn (II) (40%–70%)	Yadav et al. (2023a)
Cellulose-Ag		Cd and Cr	Tavker et al. (2021)
Microcomposite by using a mixture of CFA and ISA		Malachite green (MG)	Kumar Yadav et al. (2022)
Iron oxyhydroxide@COF (FeOOH@ Tz-COF)		As (III) upto 98.4%	Guillem-Navajas et al. (2022)
Iron (III) oxyhydroxide powders with TEMPO-oxidized cellulose nanofibrils		Flouride removal	Umehara et al. (2022)
CdS/TiO_2		Acid blue dye	Qutub et al. (2022)

TABLE 8 Application of different inorganic support used for the removal of pollutants from wastewater.

Inorganic support	Removal	Adsorption capacity (mg/g)/removal efficiency	References
ZnO NPs onto granular activated carbon	Pb(II)	76.7	Kikuchi et al. (2006)
Poly 1,8–diaminonaphthalene/ MWCNTsCOOH	Cd(II) and Pb(II)	101.2 and 175.2	Nabid et al. (2014)
Biochar/MgO nanocomposites	Phosphates and nitrates	835	Zhang et al. (2012)
Clay-based polymeric nanocomposites	Co(II), Zn(II), Se(IV) and atrazine	-	Scocchi et al. (2007)
Halloysite decorated with ZnO	MB dye	90%–97%	Choudhary et al. (2023)
Ag supported-Montmorillonite (MMT)	MB dye	81%–95%	Choudhary et al. (2021)
Kaolin/ZnO nanocomposites	Chloride, Cr(VI), Fe(III), COD, biological oxygen demand (BOD)	Cr(VI): (100%), Fe(III): (98%), COD: (95%), BOD: (94%), Chloride: (78%)	Mustapha et al. (2020)
Waterworks and sewage sludge coated with siderite NPs		CR with maximum adsorption value: 9,416 mg/g	Alshammari et al. (2020)
Magnetic biochar (pyrolysis of sewage sludge and biomass)		Cu (II)	Zhao et al. (2021)
Magnetite-Zeolite nanocomposite	BOD	99.96%	Kovo et al. (2023)
	COD	99.88%	
	Total organic carbon (TOC)	99.87%	

efficiency and economical cost. These metal oxide NPs mainly include nano zero-valent iron (nZVI), Fe_2O_3, Al_2O_3, MnO, TiO_2, MgO, CeO_2, ZnO, and TiO_2 (Naseem and Durrani, 2021; Aragaw and Ayalew, 2023; Singh et al., 2023b; Inamdar et al., 2023). Applications of all these NPs for the remediation of wastewater contaminants are shown in Table 5.

5.2.1 Nanosized iron

Nanosized iron is selected for its reactivity, cost-effectiveness, adsorbing capacity eco-friendliness for contaminant removal from water. These are reported to be very helpful in removing contamination because of their area, size, and dispersion (Justin et al., 2017; Gupta et al., 2022). Kanel et al. (2006) conducted a comprehensive investigation on the application of nZVI across a broad spectrum of pH levels for the purpose of remediating As(V) contamination (Kanel et al., 2006). Another report demonstrated that nZVI exhibits notable reactivity, substantial surface modification, biocompatibility, and favorable magnetic properties (Xu et al., 2012).

Generally, nZVI exhibits the outer layer (Fe oxides) and inner layer Fe [0] in its structure. The inner layer (Fe [0]) reacts with water and oxidizes to form iron oxides, and finally forms different corrosion products like goethite, aragonite, and lepidocrocite (i.e., α-, β- and γ-FeOOH) (Mu et al., 2017). Liu et al. (2013) studied that all these corrosion products show excellent adsorption ability towards various pollutants. Wen et al. (2014) used a co-precipitation process and reported the phosphate adsorption capacity of 245.65 mg/g onto nZVI. Figure 7 shows the oxidation and reduction of various metallic compounds on the surface of nZVI, while Figure 8 shows the various forms of nZVI for environmental applications.

5.2.2 Nano-sized metal oxide

In recent years, nano-sized magnetic adsorbents have emerged as a significant field in nanoscience (Chen et al., 2022). Researchers studied nano-sized metal oxides towards various metallic contaminants like arsenic, cadmium, uranium, chromium, and phosphate toxins, and organics. Heavy metals, dichlorophenol, and MB were removed from water using a variety of nano-sized metal oxides that were all effective in their own ways (Chavali and Nikolova, 2019; Zhou et al., 2019; Gakis et al., 2023). Table 6 shows the applications of metal oxide NPs for removing wastewater pollutants.

Fagan et al. (2016) studied that endocrine-disrupting compounds, cyanotoxins, and antibiotics get removed by nano-sized metal oxide TiO_2. Nano titanium oxide and copper oxide are utilized for electrocatalytic oxidation of organic compounds and chemical oxygen demand (COD) removal studied by Chang et al. (2009). In water purification, their pollutant removal utility was studied by various researchers, for example, pesticides, dyes, polymers, phenolic compounds, aldrin, polychlorinated biphenyls, *etc.* (Arabatzis et al., 2002; Cozzoli et al., 2004; Ahmed et al., 2011; Tolcha et al., 2020).

5.2.3 Noble metal nanoparticles

Certain transition metals (Au, Ag, Pt, and Pd) act as noble metals. The significant change in ionization energy and oxidation potential at the nanoscale range make them useful in many novel reactions. Organic contaminants are easily identified by gold and silver nanoparticles (AgNPs) because of their unique optical properties (Alberti et al., 2021; Nadaf et al., 2022). Noble metal NPs were synthesized by the reduction method through controlled nanocrystal nucleation with a stabilizing agent. The utilization of

TABLE 9 Nanoparticles/nanomaterials and nanocomposite-based membranes for wastewater treatment.

Nanocomposite membrane	Performance (L/m2 h bar)	Properties	References
Nano-TiO_2	12.2	Fouling resistance (FR), anti-bacterial, concurrent separation, and photocatalytic oxidation, TiO_2 nanowire growth via hydrothermal processing photocatalytic under UV degradation of pharmaceuticals	Yang et al. (2012)
Anatase/titanate nanosheet composite	-	Photo-catalysis self-cleaning- recovery of water flux through the membrane	Liu et al. (2016)
Immobilized ZnO/AlNPs	118–1698	Better hydrophilicity, water permeability, FR, flux recovery, mechanical stability, thickness-controllable coating, and pore size reducing	Hong and He (2014)
CNTs-embedded membrane	-	FR	Chen et al. (2012)
Graphene	21.8	Ultra-thin sheets, High retention (>99%) for organic dyes and for ion salts retention rate is moderate (approximately 20%–60%)	Han et al. (2013), Mahmoud et al. (2015)
GO	80–276 Lmh/MPa	GO-based membrane 4–10 folds higher flux range than commercial NF Cross-linked GO sheets made by a layer-by-layer process	Hu and Mi (2013), Cao et al. (2014)
SiC-SiC	0.06	Free and uniform membranes and approx. defect-free SiC	König et al. (2014)
Ag NPs	9.5 m^3/m^2 day atm	AgNPs deposition via layer-by-layer method	Kawada et al. (2014)
Ag/TiO_2 nanofiber	5–20 at 1–4 bar	99.9% bacteria inactivation and 80% dye degradation under solar irradiation within 30 min	Liu et al. (2012b)
Al_2O_3/SiC	10–3000 at 10 bar	Reduction of defect density on the surface	Facciotti et al. (2014)
Polyvinyl alcohol/polypropylene	32,346 L/m^2 h, 0.24 bar	Combined solution and melt electrospinning methods to achieve a smaller avg. pore size than nonwoven membranes	Li et al. (2015)
Poly (vinylidene fluoride)/hydroxyethylmethacrylate	-	Electrospun nanofibrous membrane coated with a surface-charged chitosan polymer, Enhanced hydrophilicity, and improved flux	Nasreen et al. (2014), Ramakrishna and Shirazi (2015)
Cellulose acetate nanofiber	3540	10×higher flux than commercial membranes	Soyekwo et al. (2014)
Polyethylene terephthalate	0.1–0.21 mL/cm^2 s at pH 4–8	Reversible pH-responsive permeation	Pan et al. (2014b)
Polysulfone/poly [2,2'-(mphenylene)-5,5′-dibenzimidazole]	355 L/m^2 h	Enhanced porosity, hydrophilicity, and thermal stability	Eren et al. (2015)
Polyvinyl chloride and polyvinyl formal	52–323 L/m^2 h at 0.1 MPa	Enhanced FR	Pezeshk et al. (2012), Fan et al. (2014)
Poly (vinylidene fluoride-hexafluoropropylene)-loaded with yttrium carbonate and Fe_3O_4		Removed arsenite (92.82) and arsenate (137.08) mg g−1	Salazar et al. (2022)
Cu-Al LDH@ polyvinylidene fluoride (PVDF) membrane (Cu-Al LDH/PVDF)	Adsorption capacity: 17.36 mg g^{-1}	Erythrosin B dye	Abbasi et al. (2021)
Boron nitride nanosheets/PVDF	MB dye: 142.86 mg g^{-1}	100% removal of MB 2.2 times higher than the PVDF alone	Bangari et al. (2022)
Mesoporous TiO_2/PVDF		Photocatalytic membrane used for removal of CR: 84%/71% and Reactive Yellow 145 (RY 145): 100%/87%	Erusappan et al. (2021)
Chitin nanowhisker/PVDF (1%:15%)	72.6 mg g^{-1}	IR dye removed upto 88.9%	Gopi et al. (2017)
NZVI/PVDF		Removed RhB (~80%), 2,4-dichlorophenol (2-CP) and 4-nitrophenol (4-NP) almost 100% within half an hour	He et al. (2020)

(Continued on following page)

TABLE 9 (*Continued*) Nanoparticles/nanomaterials and nanocomposite-based membranes for wastewater treatment.

Nanocomposite membrane	Performance (L/ m2 h bar)	Properties	References
PVDF/HDTMA (hexadecyltrimethylammonium bromide)-modified clinoptilolite		Reactive red 120 (RR120) was separated up to 98.5%	Hosseinifard et al. (2020)
Fe_3O_4/PVDF	Water flux: 175.8 L m^{-2} h^{-1} (high)	MB removed up to 97.6%, good hydrophilicity, and excellent FR properties due to the Fenton reaction	Huang et al. (2020)
Fe_3O_4/molecularly imprinted resorcinol -HCHO -melamine resin (Fe_3O_4/MIRFMR)/PVDF	Water flux: 42.5 L/m^2 h	Removal of RhB up to 95.8%, Flux recovery ration:88.9%, FR, better wettability	Jahankhah et al. (2021)
ZIF-67@PVDF ultrafiltration membrane		Removed dyes: orange II (97.3%), MB (98.2%), and RhB (90.5%). excellent FR performance, good reusability, and stability	Liu et al. (2021a)

polymers and surfactants for enhancing stability was also demonstrated (Geng et al., 2022).

In the presence of pesticides, the gold nanoparticle surface will change with indoxyl groups at the ppt level. Contaminants are efficiently eliminated through the implementation of sensing, monitoring, and photocatalysis techniques facilitated by bimetallic nanoparticle-based electrodes (Behera et al., 2020; Rajeev et al., 2021; Białas et al., 2022). The role of the anti-bacterial activity and their sterilization effect (to sterilize surgical masks and textile fibers) was also studied (Xiu et al., 2011). Various pollutants like pesticides (Chaudhari et al., 2023), dyes, and halogenated compounds could be photo-catalytically degraded by noble metals (Quan et al., 2015).

5.3 Nanocomposites in water treatment

In the field of NMs, various nanocomposites were used as hosts and infused NPs and showed their significance in several reactions. Besides it, nanocomposites also reduce the environmental discharge of NPs (Hnamte and Pulikkal, 2022). These compact materials are used in the nanoscopic and mesoscopic scales, and their different varieties are discussed below.

5.3.1 Nanocomposites of organic supports

The unique characteristics of polymers, including porous structures, exceptional mechanical strength, and the presence of functional groups, make them highly suitable for use as supports in polymer-based nanocomposites (PNCs) for wastewater treatment. To eliminate heavy metal ions, PNCs (grafted magnetic nanoparticles) were prepared by grafting polymerization techniques (Uwamungu et al., 2022). Several research has been done on the fabrication of PNCs in which polymers and precursors of NPs are directly joined with NPs in direct compounding. They are synthesized by *in-situ* precipitation and nucleation methods. The potential applications and removal of contaminants of various nanocomposites are summarized in Table 7.

5.3.2 Nanocomposites of inorganic supports

For nanocomposites CNTs, naturally occurring minerals (zeolite, clay) and activated carbon are used as inorganic supports (Veeman et al., 2021). These adsorbents are extensively used in wastewater treatment facilities (Table 8).

5.3.3 Nanocomposite membrane for wastewater treatment

The unique properties of membranes such as long life, low cost, and high mechanical, chemical, and thermal stability, were used for water decontamination. Their low cost and less energy consumption make them useful at the industrial level (Shehata et al., 2023). They occur as conventional nanocomposite membranes, thin-film nanocomposites, and surface-coated nanocomposite membranes. The conventional nanocomposite membrane was prepared by the phase inversion method. A team led by Liu et al. (2015) studied the use of thin-film nanocomposite, in the RO/NF membrane through the phase inversion as well as the interfacial polymerization method. In surface-coated nanocomposites, NMs are used on the membrane surface by self-assembly, chemical grafting, *in-situ* deposition, and adsorption methods (Zhang et al., 2011b; Chaturvedi et al., 2022). Table 9 shows the recent development of inorganic and organic nanomembranes.

6 Conclusion

Nanotechnology and nanoparticles have played an important role in environmental cleanup and wastewater treatment in the 21st century. Due to its remarkable features, it has gained huge attention for the remediation of various organic pollutants like dyes, pesticides, heavy metals, pathogenic microorganisms, *etc.* The increase in the popularity of nanoparticles for remediation is due to their, surface-based phenomenon, high efficiency, and easy surface functionalization. To, date carbon NMs, metal, metal oxide nanoparticles, and nanocomposites have been used widely for wastewater treatment. The magnetic nanoparticles and photocatalytic nanoparticles are of huge importance as magnetic nanoparticles could be easily recovered while the photocatalytic materials could completely mineralize the toxic pollutants. Recovery after the application prevents the loss of the nanoparticles making the process highly effective. Indeed nanoparticles have a huge potential for the remediation of both organic and inorganic pollutants from wastewater.

Author contributions

MC, HS, VS, and NA: Original draft, review editing, methodology, software SK, DS, VY, and AP: Supervision, review editing, project administration, investigation, funding acquisition, resources. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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