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Review Article

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Advances and Opportunities of Nano materials in Wastewater Treatment

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Abstract

Water is the most important resource for life and its availability with natural water quality is essential for environmental sustainability. However, the world is facing water crisis especially due to water contamination of water bodies through discharge of wastewater emanating from urban and industrial areas. Extensive urbanization and industrial development with increasing human population intensified overexploitation and severe contamination of water resource which leads to detrimental impact on aquatic ecosystem and water quality. Therefore, it is important to treat wastewater before its final discharge into the water bodies to ensure conserving natural water and aquatic environment. Various conventional water treatment techniques are available and being used for treating wastewater, however, these are ineffective to treat the whole wastewater generating due to more gap between wastewater generation and treatment facility available and even their cost effectiveness. Limits of traditional technologies and materials for removing undesired and hazardous chemicals from water have encouraged the development of more effective and long-term solutions. Thus, more advanced technologies are emerging to treat wastewater more effectively. Nanotechnology has emerged as an advance technology for effective wastewater treatment. Main benefit of using nanomaterial-based technology is its reusability and effectiveness. Various forms of single or hybrid nanomaterials have been widely used to remove various contaminates including metals, microorganisms, and organic contaminants from wastewater. This review was based on the advancement and application of nanotechnology for effective wastewater treatment and conserve water quality.

Keywords

Contaminants, Nano materials, Nanotechnology, Wastewater, Water quality

Introduction

Fresh water is very essential for survival of all living beings on the earth planet. Water contamination is now becoming a global issue due to improper sewage disposal and industrial effluent, dumping of solid waste and agricultural runoff [1, 2]. Discharge of industrial effluents and sewage containing organic matter into aquatic environment effects water quality as well as aquatic animals and plants. Water contamination leads to degradation of aquatic ecosystem and human health hazards through water borne diseases. Water contamination affects socio-economic condition, development and social perspectives of the public and society [3]. Removal of waste water pollutants emanating from industrial processes is become a major challenge [4, 5]. Various technologies for wastewater treatment are available and being used for contaminants removal based on physical, chemical, and biological processes. However, the most of traditional technologies have their own disadvantages and limitations including high energy requirements, insufficient pollutants removal, and the formation of hazardous sludge during the wastewater treatment process [6, 7]. Conventional technologies are not effective in removal of metals, nitrogen, phosphorous, and other contaminants from waste water [7, 8] as these techniques involves chemicals and require energy for operation, maintenance, skilled person to operate and high capital cost for establishment. Nanotechnology with advanced nanomaterials are more effective for treating wastewater due to its nano size, high reactivity, greater solution mobility [9] porosity, strong mechanical property, and hydrophobicity [10, 11]. Most of the metals like Pb, Mo, Hg, Cd, Cu, organic and inorganic contaminants, and infectious microorganisms can be eliminated using nanomaterials [12, 13]. In essence, nanotechnology manipulates molecules and atoms to produce a novel design, object, or system with improved electrical, magnetic, optical, and mechanical properties [14, 15]. Nanomaterials such as nanophotocatalysts, micromotors or nanomotors, nanomembranes, and nanoadsorbents (which have a high sorption capacity and are used in a variety of water treatment applications) as well as imprinting polymers have recently made significant advances in the treatment of contaminated water [1]. The present review was focused on the advancement and application of nanomaterials in wastewater treatment for preserving and conserving water resources and aquatic ecosystem. In addition, the nanomaterials' limitations, benefits, drawbacks, and future prospects have been discussed.

Wastewater and water quality

Wastewater is produced from different sources, including sewage, industrial waste, commercial waste, and agricultural waste. Wastewater is characterized by its physical characteristics, chemical composition, and microbiological activity [16-18]. Almost all of the main sources, especially industries, need safe water, but in exchange, a lot of contaminated water is generated and discharged into the aquatic bodies which leads to water contamination [19]. Generally, wastewater comes from natural life processes or is contaminated by human use [20]. In general, wastewater is divided into sewage wastewater and non-sewage wastewater [21]. Stormwater runoff, household, agricultural, and industrial wastewater are the four main types of wastewater [22]. Stormwater runoff wastewater is water that flows above the street or open surfaces after a heavy rain, a storm, or a flood [23]. Domestic wastewater is produced by household activities [24]. Domestic wastewater is categorized by its color like black, grey, and yellow wastewater [25]. Black colored wastewater the most polluted type of household wastewater, which comes from toilets, sinks, and kitchen dishwashers [26]. Less polluted domestic greywater is discharged from washing machines, bathtubs, and bathroom sinks [27]. Yellow water is pure urine water with no faeces, toilet paper, chemicals, or even food particles in it [25]. In many watersheds, agriculture runoff is a major pollutant. When water runs off fields during surface irrigation, agricultural wastewater is known as irrigation tailwater [28]. Industrial wastewater is water containing dissolved and suspended pollutants from manufacturing, cleaning, and other business processes [29]. Figure 1 represents the normal composition of wastewater.

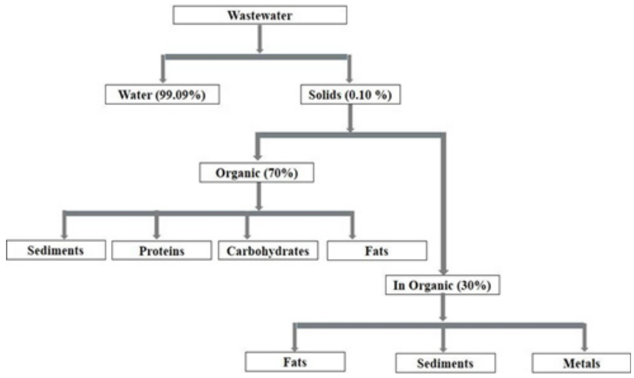

Figure 1: Composition of wastewater.

Wastewater treatment technology

Conventional wastewater treatment techniques, such as reverse osmosis, distillation, coagulation- flocculation, bio-sand, and filtration, are insufficient for removing all contaminants. Recent advances in nanotechnology has the potential to make water purification more cost-effective, more effective in removing impurities, and reusable [30]. Various types of nanomaterials, such as polymeric nanoparticles (NPs), carbon-based nanomaterials, metal NPs, zeolite, self-assembled monolayer on mesoporous substrates biopolymers, and others, are used in the treatment of wastewater [31]. Adsorption, photocatalysis, nanofiltration, sensing, disinfection, and pathogen control are some of the processes involved in treating wastewater using nanotechnology.

Nanoadsorbent

In adsorption process molecules of a gaseous liquid or dissolved solid adhere to the porous membrane to make a coating or film on a solid surface [32]. Carbon nanotubes (CNTs), activated carbon, NPs and polymeric nanoadsorbents are the main categories of nanoadsorbents [33]. Carbon CNTs have replaced activated carbon as an adsorber for water filtration. Adsorption capacities, chemical stability, accessibility, and thermal stability enables carbon-based nanomaterials more feasible for effective water treatment [34]. According to Elsayed et al. [35], nano-hydroxyapatite can be used to treat wastewater, and its effectiveness in these applications may be improved by the addition of another chemical, such as humic acid. Nanosorbent materials show high efficiency and faster rates to removal of contaminantes from wastewater [36]. Removal of different water contaminants by using various nanoadsorbents are depicted in Table 1.

Nano membranes

One of the most essential water purification processes is membrane filtration. Membranes provide a physical barrier to contaminants based on their pore size and molecular size. Inorganic contaminants are removed from wastewater using nano membranes. Nanomembranbe filter used to remove of toxic particles from water resource and measure the safety level of water [47]. There have been many studies on the immobilisation of metallic NPs on membranes for dichlorination and degradation of a toxic substance with

Table 1: Removal efficiency of contaminants by different nanoadsorbents.

Nano Material	Contaminant	Adsorption Capacity (mg/g)	Reference
Single-walled CNT	Cr (VI)	2.35	[37]
Multiwalled CNT	Cr (VI)	1.26	[37]
Multiwalled CNT	Methylene blue	59.7	[38]
Graphene	Methylene blue	204.08	[39]
CuO-ZnO nanofibers	Congo red	126.4	[40]
ZnO	Direct blue 78	34.48	[41]
TiO_2 NPs	Reactive Red 195	87	[42]
GO/Fe_3O_4	Arsenic (V)	5.27	[43]
Ash with chitosan	Zinc	55.22	[44]
Zeolite	Cr (III)	163.9	[45]
Red-Mud Fe	Cr (III)	17.8	[46]

new properties like NPs hindrance, high reactivity, lack of agglomeration, and surface reduction [48]. Membrane filters made of nanofibers with a large surface area, a high surface-to-volume ratio, porosity, and inter connectivity produces electro spin. This membrane can filter micron-sized particles and germs and viruses effectively [49]. Arsenate in water can be removed by chitosan nanofiber [50]. Nanofibers are created by electrospinning a polymer, ethylene oxide, Fe^{3+}, and chitosan, then crosslinking with ammonia vapour. Kang et al. created a bio-based nanofiber barrier to remove oil, organic contaminants, and water soluble dyes [51]. Nanofibers can remove oil in water emulsion, soluble organic contaminants, and organic solvents. These membranes can be reused after a minor solvent wash. Nanocomposites membranes are another type of filter based on membranes that show potential for removing contaminants. NPs are integrated into a matrix of macroscopic components and their combinations to improve permeability, selectivity, and antifouling properties of membranes to be used for filteration process [52]. Polyethylenimine-grafted graphene oxide, a new addition that decreased membrane fouling and increased filtration capacity, was used by Zhang et al. to create a nanocomposite membrane.

Nano Photocatalyst

The term "photocatalysis" is derived from the Greek terms "photo" and "catalysis" and refers to the decomposition of chemicals in the presence of light [53]. Photocatalytic technology is used to reduce water pollution. Photocatalysts oxidise a variety of pollutants in water by harnessing the energy from sunlight. Organic and microbial pollutants may be removed by this method [54]. Heterogeneous photocatalysis occurs in gas, aqueous, etc. phases. This process involves transferring fluidic reactants to the surface and adsorbing a small number of reactants [55]. In aquatic environments, transition metals are also toxic and can be reduced by photocatalysis. Solar photocatalytic redox processes are used to remove inorganic pollutants from waste water [56]. Generally, nanophotocatalysts have a physico-chemical stability, low cost, and ecofriendly. Many nanophotocatalysts like metal sulfide materials, ZnO, copper-based materials have a low chemical stability due to photocorrosion [57]. List of photocatalysts reported for degradation of organic pollutant and reduction of heavy metals was shown in table 2. Breakdown process of pollutants and its route in the presence of light was shown in Figure 2.

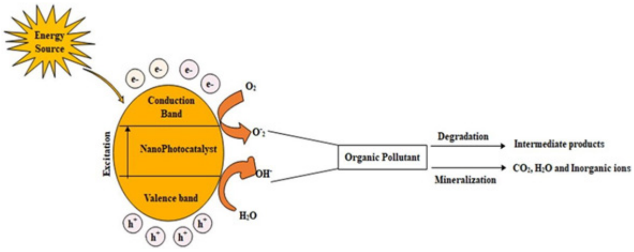

Figure 2: A potential pathway for pollutant degradation in the presence of light.

Table 2: List of nano photocatalysts used for degrading pollutants.

Nano photocatalyst	Pollutant	Degradation (%)	Reference
CuO–TiO_2/ rGO	Methyl orange	89	[58]
α-Fe_2O_3	Methylene blue and Rhodamine B	96	[59]
TiO_2–2- naphthol complex	Cr(VI) reduction	100	[60]
Zn-doped Fe_3O_4	Rhodamine B and cephalexin	97	[61]
Ti–SBA-15	Eriochrome black T	89	[62]
MoS_2/$Fe_3O_4$$MoS_2$/$Fe_3O_4$	Rhodamine B	90	[63]
TiO_2	Methylene Blue	90	[64]
TiO_2	Methylene Orange	99	[65]

Antimicrobial Nanomaterials

In the current scenario, NPs can potentially be used as antibacterial agents. These NPs interact with microorganisms and kill them through a variety of mechanisms, like interruption of transmembrane, electron transfer, cell damage, generation of reactive oxygen species and production of harmful secondary metabolite [66]. Various nanomaterials have antimicrobial properties, such as Silver (Ag) NPs which discharge Ag ions and bind to the thiol groups in the bacterial protein leading to microbial cell death. Ag ions damage and effects DNA replication. It has been shown that adding Mg to ZnO can increase the material's photocatalytic activity, which enhances its antibacterial properties [67] (Table 3).

Nano and Micromotors

Modern technology has led to the development of nano/micromotors, which can transform energy from various sources into machine-driven force and carry out a variety of activities to achieve predetermined objectives. These new motors can be powered by fuel or without fuel, and they can be used in a lot of interesting ways [74]. Table 4 shows nano/

micromotor mechanisms for treating water contaminants and environmental applications.

Applications of Nanomaterials

Nanomaterials might be utilized in the water treatment industry and other sectors. Nanomaterials are gaining favour in wastewater treatment. Iron hydroxide material is combined with exchange- based resin material and titanium NPs. Iron oxide nanomaterials remove arsenic from drinking water very effectively in developed countries [82, 83]. Nanomaterials like CNTs and magnetic nanowires, which have distinct physical, electrical, and chemical properties, can be employed as components of sensors. Nanomaterial-based sensors may detect different contaminants because of their optical properties [84, 85]. Water contaminants are responsible for environmental pollutions. Environmental protection is assisted by the nanomaterial composed of polymers. CNTs, zeolites, and self-assembled layers on mesoporous supports nanomaterials that can function as sorbents to control mesoporous ceramics and indicates a successful technique for removing metals and anions from drinking water [1, 86]. Antimicrobial properties can be found in several nanomaterials. Among the characteristics of this class of materials are low oxidation, water inertness, and harmless byproducts. Examples include AgNPs, fullerene, TiO_2, CNT-based nanocomposite, etc. [87]. Metal oxide NPs are great oxidation catalysts. They react more catalytically with pollutant molecules and turn them into products that are beneficial to the environment [88].

Challenges and Opportunities

Emerging nanomaterials currently represent major challenges for wastewater treatment [89]. Several approaches, including photocatalytic, adsorption, and nanosorbents, are used to detoxify polluted water with nanomaterials [90]. These procedures require certain changes to be more effective. The biggest problem is the lack of knowledge about how nanomaterials are released into the environment [91]. There is also a problem with regard to human health due to the toxicological effects of these elements. Nanotechnology's challenges are NPs toxicity and exposure danger. The first major concern is a biological or chemical effect on the environment or people. NPs leakage, spillage, flow, and concentration can affected people and the environment [92]. They can be harmful to people and the environment. NPs can enter through the skin, inhalation, ingestion, etc. Heart, brain, kidneys, liver, nervous system, spleen, and bone marrow can be affected. The membrane technique effectively treats wastewater, but few studies have been done on it. After doing work/filtration, the membrane's pores may block, reducing its efficiency. The main disadvantages of nanosorbents is their reusability, hence it is required to synthesize nanomaterials that efficiently remove contaminants from wastewater and have a simple recovery method. Designing an experiment to determine the intermediate molecules created by these processes is a crucial requirement. In addition, cost-effective evaluation of nanomaterials necessitates the ongoing development of cost-effective, complicated nanomaterial evaluation methodologies.

Table 3: Antimicrobial nanomaterials and their water treatment potential.

Nanomaterials	Microorganisms Removed	Removal Efficiency (%)	Reference
Silver nanomaterials loaded kaolin clay	*Escherichia coli*	80	[68]
Silver nanomaterial in polysulfone membranes	*Escherichia coli*	92	[69]
Carbon nanoparticles	*Escherichia coli*	6 log reduction (25 mg/50 mL concentration)	[70]
Silver nanomaterial loaded chitosan cryogels	*Bacillus subtilis and Escherichia coli*	3 log reduction (silver content – 7.5 mg/g)	[71]
Ag-TiO_2 compound	*Escherichia coli*	-	[72]
Ag doped TiO_2-chitosan (STC)	*Escherichia coli, S. aureus, and P. aeruginosa*	-	[73]

Table 4: Nano/micromotor mechanisms for treating water contaminants and environmental applications.

Nanomotors	Applications	Mechanism	References
Zn, Al/Pd micromotors	pH controlling	speed-pH dependence	[75]
Polymer capsule motors	Oil remediation	Surface tension induced cargo towing	[76]
Au/Pt nanomotors	Detection of silver ions	silver-induced acceleration	[77]
Ir/SiO_2 Janus motors	Detection of hydrazine	Speed-concentration dependence	[75]
Ag-based Janus MIP microparticles	solid-phase extraction	Molecular imprinted polymer recognition	[78]
Hydrophobic agglomerates of pollutants	Increased diffusion of pollutants	Surface tension induced	[79]
Au/Pt nanomotors	DNA detection	DNA hybridization through using Ag nanoparticle	[80]
SAM modified Pt micro engines	Oil removal	Hydrophobic interactions with oil droplets	[81]

Conclusion and Future Perspectives

Chemical and biological pollutants must be removed from industrial effluent using modern wastewater purification processes. Water treatment technologies based on nanomaterials are critical in this context. Nanomaterials have specific physico-chemical properties and effectively remove pollutants. NPs are a versatile in targeting and eradicating various kinds of impurities (organic, inorganic, biological, etc.). Nanomaterials are crucial for the adsorption and filtration of contaminants. Furthermore, NPs have a crucial role in antibacterial activity. Nanomaterial technologies, such as nanostructured catalytic membranes, nanosorbents, and others are extremely effective, ecofriendly, and less time and energy to operate. Nanomaterials have excellent efficiency because of their rapid reaction rates. However, they are not inexpensive, and they have not yet been used on a large scale in the wastewater treatment industry. Nanotechnology offers the opportunity; the features of NPs are particularly well-suited to efficient water treatment. A longer study may focus on enhancing the functional properties of nanomaterials for detecting and treating pollutants and on their environmental effects and risks. On the other hand, nano-engineered materials hold great promise for water revolutions, notably for point-of-use techniques, decentralized water treatment technologies, and very biodegradable toxins. In addition, the commercialization and cost issues of various wastewater treatment systems must be considered. The various applications of nanomaterials can give a substantial contribution to the global water supply.

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