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Review

Role of nanomaterials in water treatment applications: A review

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HIGHLIGHTS

- Use of nanomaterials (NMs) in water treatment has been reviewed.
- Carbon nanomaterials, nano metal oxides and nano composites are reviewed.
- Adsorption, photocatalytic and antimicrobial properties of NMs are reviewed.

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ABSTRACT

Water pollution by various toxic contaminants has become one of the most serious problems worldwide. Various technologies have been used to treat water and waste water including chemical precipitation, ion-exchange, adsorption, membrane filtration, coagulation–flocculation, flotation and electrochemical methods. From past few decades, nanotechnology has gained wide attention and various nanomaterials have been developed for the water remediation. In the present review article, various nanomaterials have been reviewed which have been used for water decontamination. The special emphasis in the review has been given on adsorption, photocatalytic and antibacterial activity of nanomaterials.

Contents

Abbreviations: CNTs, carbon nanotubes; SWCNTs, single walled carbon nanotubes; MWCNTs, multi walled carbon nanotubes; CS, chitosan; CR, Congo red; BET, Brunauer–Emmett–Teller; NOM, natural organic matter; SW, sea water; BW, brackish water; OL, old leachates; YL, young leachates; DOC, dissolved organic carbon; THMs, trihalomethanes; SEM, scanning electron microscope; TEM, transmission electron microscope; PAC, powdered activated carbon; CNCs, carbon nanocrystals; OLA, olaquindox; TC, tetracycline; DOM, dissolved organic matter; NR, neutral red; MV, methyl violet; RhB, Rhodamine B; MO, methyl orange; GO, graphene oxide; rGO, reduced graphene oxide; GNs, graphene nanosheets; NMOs, nano metal oxides; MNPs, magnetic nanoparticles; MB, methylene blue; IOT, iron ore tailings; FHO, ferric hydrooxide; SDS, sodium dodecyl sulphonate; PGA, poly(γ-glutamic acid); TCE, trichloroethylene; MTP, metroprolol; GAC, granular activated carbon; P(A-N)/AT, poly(acrylic acid-acrylonitrile)/attapulgite; P(A-O)/AT, poly(acrylic acid-acryloamidoxime)/attapulgite; AA, acrylic acid; AN, acrylonitrile; AT, attapulgite; SCS, self-propagating solution combustion synthesis; MG, malachite green; POSS, poly octahedral silsesquioxanes; TPP, triphenylphosphine; OVS, octavinylsilsesquioxane; AO, amidoxime; Gt, graphite; GtO, graphite oxide; UV, ultra violet; ROS, reactive oxygen species; CFU, colony forming units; GSH, glutathione; ZOI, zone of inhibition.

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1. Introduction

Clean water is one of the most important elements for all living organisms to sustain life. However, due to the rapid pace of industrialization and tremendous increase in the population, the contamination of water resources has occurred globally [1,2]. Besides other needs, the demand for water has increased tremendously in agricultural, industrial and domestic sectors consuming 70, 22 and 8% of the available fresh water, respectively and this has resulted in the generation of large amounts of wastewater [3–5] containing a number of 'pollutants'. Some of the important classes of aquatic pollutants are heavy metal ions and dyes, and once these enter into the water, water is no longer safe for drinking purpose and sometimes it is very difficult to completely treat the contaminated water [6,7]. Aquatic pollutants are often very dangerous for living beings, and also affect the ecosystem. Therefore, the removal of these pollutants from contaminated water is an urgent need in order to prevent the negative effects on the human health and to the environment.

From past few decades, various techniques have been developed for treating the waste water [8–13]. Among them, most important methods are solvent extraction, micro and ultrafiltration, sedimentation and gravity separation, flotation, precipitation, coagulation, oxidation, evaporation, distillation, reverse osmosis, adsorption, ion exchange, electrodialysis, electrolysis, etc. From above mentioned techniques, adsorption is one of the considerable techniques for treating the waste water, because of its easy operation, low cost and the availability of a wide range of adsorbents. Besides, adsorption can also be applied for the removal of soluble and insoluble organic, inorganic, and biological pollutants. Additionally, adsorption can also be used for source reduction and reclamation for potable, industrial, and other water purposes. In spite of these facts, adsorption has certain limitations such as it could not achieve a good status at commercial levels. Probably, it is due to the lack of suitable adsorbents with high adsorption capacity and limited use of adsorbents on commercial scale columns. Besides, a single adsorbent cannot be used for removing all kind of pollutants. Different adsorbents are used for different pollutants based on their properties. A comparison of adsorption method was carried out with other water treatment technologies. The order of cost effectiveness is adsorption > evaporation > aerobic > anaerobic > ion exchange > electrodialysis > micro- and ultra-filtration > reverse osmosis > precipitation > distillation > oxidation > solvent extraction [14]. It was observed that, in spite of some limitations, adsorption will be considered a good water treatment technology in the near future. Much work has been conducted on the removal of different pollutants from water by using adsorption in batch mode process [14,15]. Initially, activated carbon was used for the removal of pollutants from water, which has been replaced by some cost-effective adsorbents [16–18]. In the last two decades, nanotechnology has emerged significantly with its applications in almost all branches of science and technology. As a matter of fact, various nanomaterials have been prepared and used for the removal of aquatic pollutants [19]. In view of the importance of water quality and emerging utilities of nanotechnology, attempts have been made to discuss various aspects of water treatment by adsorption using nanomaterials. In this regard, promoting nanomaterials presents opportunities to develop local and practical solutions for tackling global water pollution. This review article presents a brief overview of the technical applicability of different nanomaterials for removing various aquatic pollutants.

Although many excellent review articles have been published so far discussing the importance of nanomaterials in water treatment and environmental remediation, but some of them are only a material and/or adsorbent-specific (e.g., CNTs, graphene-based nanomaterials, nano metal oxides, nano zerovalent iron, cellulose nanomaterials [20–26]) or an adsorbate specific (e.g., metals [22,24,27], dyes [28], pharmaceuticals and personal care products [29]). One of the aims of the present review is to compile the important findings of different types of nanomaterials, used in water treatment either as adsorbents, photocatalysts and/or antibacterial agents, for the removal of important aquatic pollutants. A summary of relevant published data with some of the latest important findings, and a source of up-to-date literature is presented and the results have been discussed.

2. Nanomaterials as adsorbents for water treatment

Nanoadsorbents are nanoscale particles from organic or inorganic materials that have a high affinity to adsorb substances. Because of their high porosity, small size, and active surface, nanoadsorbents not only are capable of sequestering contaminants with varying molecular size, hydrophobicity, and speciation behavior, but also enable manufacturing process to consume raw materials efficiently without releasing its toxic payload [30]. Nanoadsorbents not only work rapidly, but also have considerable pollutant-binding capacities. They can also be chemically regenerated after being exhausted [31]. For these reasons, scholarly interests of nanotechnology have been growing rapidly worldwide. At the nanoscale, materials show unique characteristics and, because of their small size, they possess a large surface area and 'surface area to volume' ratio [32]. These characteristics improve the adsorption capacity of the nanoparticles. In addition to the large surface area, these particles show unique characteristics, such as catalytic potential and high reactivity, which make them as better adsorbing materials than conventional materials. Because of their high surface area, nanoparticles have a greater number of active sites for interaction with different chemical species [33–35]. To get better results for the removal of pollutants from wastewater, nanoparticles are becoming new alternatives for the treatment of wastewater [36–40].

2.1. Carbon based materials

For any adsorption process, an adsorbent having large surface area, pore volume, and proper functionalities is the key to success. Currently, many different porous materials have been developed, such as activated carbon, pillared clays, zeolites, mesoporous oxides, polymers and metal-organic frameworks, showing varying extent of effectiveness in removing the toxic pollutants from air, water and soil [41–45]. Among them, carbon-based adsorbents including activated carbon, carbon nanotubes, fullerenes and