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Review article

Nanomaterials-enabled water and wastewater treatment

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ABSTRACT

With the fast development of nanomaterials and nanotechnology, environmental nanotechnology has attracted increasing concerns in the past decades. In the field of water treatment, nanotechnology exhibited great potential in improving the performance and efficiency of water decontamination as well as providing a sustainable approach to secure water supply. In this review, the current applications of nanomaterials in water and wastewater treatment were briefly discussed. The synthesis and physiochemical properties of diverse free nanomaterials, including carbon based nanomaterial, metal and metal oxides nanoparticles as well as noble metal nanoparticles, were focused on, and their performance and mechanisms towards removal of various contaminants were discussed. When concerning the large-scale application in water treatment, nanoparticles have to face some inherent technical bottlenecks such as aggregation, difficult separation, leakage into the contact water, as well as potential adverse effect imposed on ecosystem and human health. The emerging nanocomposite materials integrate the merits of functional nanoparticles and varying solid hosts of large size, and exhibit great advantages in scaled-up application. This review particularly covered the topic of environmental nanocomposites, such as those of organic and inorganic supports, nanocomposite membranes and magnetic nanocomposites. The advantages and perspectives of various nanocomposites are briefly discussed.

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1. Introduction

Our environment is under constant pressure with growing industrialization and urbanization. Among the world's top environmental problems, water scarcity has become the foremost issue facing the human race. In the coming decades, rapid population growth in developing region will continue to intensify the clean water demand from domestic, agriculture, industry and energy perspective (Pendergast and Hoek, 2011). By 2025, it was estimated that 50% of the world's population will be living in water-stressed areas (WHO, 2014). Until 2015, only around 20% of global wastewater is properly treated. In developing countries, approximately 70% of industrial wastewater is discharged without proper disposal of UN (2016). Current infrastructure for wastewater treatment, as well as for the production of safe and readily available water is difficult to keep pace with the increasingly stringent regulation and growing demand for high quality water, in both developed and developing country. Hence, water treatment technology featured with high efficiency and low cost is urgently required.

Recent advances in the manipulation of nanomaterials have facilitated the application of nanotechnology in water and wastewater treatment. In the past decades, water nanotechnology has received sufficient attentions as a potential supplement to the traditional treatment methods. Nanomaterials are commonly defined as materials that at least one dimension is smaller than 100 nm (Tesh and Scott, 2014). At such scale, materials often exhibit unique physical or chemical properties over their bulky counterparts. For example, nanomaterials usually have higher density of active sites per unit mass due to their larger specific surface area. In addition, nanomaterials exhibit greater surface free energy, resulting in enhanced surface reactivity. At proper size, some materials would show superparamagnetism, or even quantum confinement effect (Khin et al., 2012; Alvarez and Li, 2013b). Taken advantage of these size-dependent effects, the current water and wastewater treatment process could be greatly improved by introducing nanomaterials into the system.

Until now, numerous studies have shown that nanomaterials have vast capability and potential in water and wastewater treatment, in particular, in the areas of adsorption (Ali, 2012), membrane process (Pendergast and Hoek, 2011), catalytic oxidation (Ayati et al., 2014), disinfection and sensing (Das et al., 2015). It is a pity that most of the reported nanomaterials were in the stage of laboratory research or merely a proof of concept. One of the commercially available nanotechnology is the use of zero valent iron nanoparticles by injection (Karn et al., 2011; Tesh and Scott, 2014). This is widely used in America for groundwater remediation. Since the cost for nanomaterials are decreasing, they have become more competitive for water and wastewater treatment. However, there are still inherent disadvantages for direct use of free nanoparticles in water and wastewater treatment process. Firstly, nanoparticles tend to aggregate in fluidized system or in fixed bed, resulting in severe activity loss and pressure drop (Lofrano et al., 2016). Secondly, it is still a challenging task to separate most of the exhausted nanoparticles (except for magnetic nanoparticles) from the treated water for reuse. Apparently, it would be undesirable in terms of the economical consideration (Al-Hamadani et al., 2015; Qu et al., 2013c). Thirdly, the behavior and fate of the nanomaterials in water and wastewater treatment process are not fully understood, and the impact of nanomaterials on the aquatic environment and human health is a major issue that could hinder the application of nanotechnology (Dale et al., 2015; Varma, 2012).

To avoid or mitigate the potentially adverse effect brought by the application of nanotechnology, it is desirable to develop a material or a device that could minimize the release or mobilization of the nanomaterials while maintaining their high reactivity. The development of nanocomposite is proved to be an effective and promising approach. Nanocomposite is commonly fabricated by loading desired nanoparticles onto various supporting materials, such as polymers or membranes. It could be defined as a multiphase material which at least one dimension of the constituent phases is <100 nm (Tesh and Scott, 2014). Some of the reported nanocomposites were highly efficient in water decontamination, recyclable, cost-effective and compatible with existing infrastructure (Lofrano et al., 2016; Yin and Deng, 2015).

This review focuses on various nanomaterials used for contaminant adsorption, separation and catalytic degradation from or in water. Both free nanoparticles and nanocomposites are involved in this paper, and some promising nanocomposites will be highlighted in the review. The fabrication and characteristics of these materials will be summarized, and the performance and mechanism of decontamination by these nanomaterials will be particularly concerned. In the end, the prospect of these nanomaterials in water treatment will also be briefly discussed.

2. Brief introduction of water nanotechnology

With the development of nanotechnology, its application in water and wastewater treatment is becoming imminent. Over the past decades, there are numerous studies available on such topic. In this section, we provided a brief review of some typical application of nanotechnology in water and wastewater treatment, i.e., adsorption and separation, catalytic oxidation, disinfection and sensing.

2.1. Adsorption & Separation

Adsorbents or membrane based separation process are two most widely used technology for polishing treatment of water and wastewater. Conventional adsorbents often face challenges such as low capacity and selectivity as well as the short adsorption-regeneration cycle, which significantly reduced the cost effectiveness of the adsorbents. Nanomaterial based adsorbents, i.e., nanosized metal or metal oxides, carbon nanotubes (CNTs), graphene and nanocomposites, often feature large specific area, high reactivity, fast kinetics and specific affinity to various contaminants. Their adsorptive performance towards certain contaminants is sometimes several magnitude higher than conventional adsorbents (Ali, 2012; Khajeh et al., 2013).

Besides adsorption, membrane separation is also a key module in the polishing treatment stage, enabling water reclamation from unconventional water sources such as municipal wastewater. Removal of contaminants by membrane separation is mainly based on size exclusion. However, there are still many obstacles to further forward membrane technology, i.e., the inherent trade-off between membrane selectivity and permeability, high energy consumption, fouling and operational complexity. To address these issues, advanced nanocomposite membranes were developed by introducing functional nanoparticles into the membrane. This new class of membrane showed enhanced physiochemical properties such as improved mechanical or thermal stability, porosity and hydrophilicity. Some exhibited unique properties like enhanced permeability, or anti-fouling, antimicrobial, adsorptive or photocatalysis capabilities (Pendergast and Hoek, 2011; Yin and Deng, 2015). Adsorption and separation nanotechnology were currently the closest to commercial maturity. More discussion concerning the