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Review

Graphene and its nanocomposites as a platform for environmental applications

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HIGHLIGHTS

- Wastes generated during industrial processes play a major role in organic pollution.
- Graphene and its derivatives have attracted significant attention in the field of water treatment.
- Their mechanisms to treat organic molecules via adsorption/degradation are described.
- Their performance in such treatment is evaluated along with the reusability and toxicity.

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ABSTRACT

Graphene is a two-dimensional nanomaterial with unique characteristics that can be used to efficiently remove organic pollutants in the aqueous system via adsorption and photocatalytic degradation. This review was organized to offer valuable insights into the mechanisms regulating the graphene and its related nanomaterials as the platform for the treatment of various organic pollutants in aqueous media. To this end, the performance variables of graphene, functionalized graphene, and graphene-supported materials are evaluated for such applications in some respects. Our discussion is extended further to describe regeneration and reuse of these nanomaterials along with future challenges encountered in their applications, especially on toxicity and stability aspects.

Contents

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1. Introduction

There are a variety of organic pollutants that exert undesirable effects or cause damage to the human as well as the environment. Organic pollutants can generally be categorized into the three major classes based on their chemical composition [1]: (1) hydrocarbons; (2) nitrogen, oxygen, and phosphorus compounds; and (3) organometallic compounds (Fig. 1). The first category includes hydrocarbon and related compounds like dichloro-diphenyl-tri chloroethane (DDT), polycyclic aromatic hydrocarbons (PAHs), and dioxins. These compounds generally have low polarities, which make them less soluble in water but highly soluble in fats. As such, they persist in the environment by accumulating in the fatty tissues of organisms. The pollutants of the second group contain heteroatoms like nitrogen, phosphorus, and oxygen in the hydrocarbon structure. These heteroatoms are responsible for the high level polarity to the related compounds. The high level polarity makes these compounds water soluble and fat insoluble. The compounds with such heteroatoms are easily dissolved by the environmental processes, which makes them less persistent. The third category includes organometallic compounds consisting of metals like lead and tin.

Of all known organic pollutants, a certain fraction is classified as persistent organic pollutants (POPs), which pose numerous environmental problems. In general, POPs are resistant to the usual photolytic, chemical, and biological degradation processes [2]. Hydrocarbons and related compounds are the major members of this family. The main sources of organic pollutants are sewage, storm water, industrial waste, agricultural activities, and accidental spillage [1]. For example, discharge of material from motor vehicles close to the road can contaminate storm water. Wastes generated during industrial processes also play a major role in organic pollution of the environment. On the other hand, agricultural activities (like spraying of pesticides) and industrial wastes are the main source of organometallic compounds in the environment [3–5].

Organic pollutants can severely affect people and the environment; therefore, it is imperative to develop effective methods of

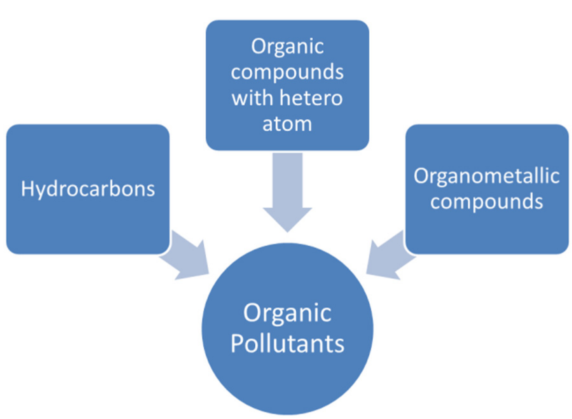

Fig. 1. Major classes of organic pollutants.

removing these pollutants. Among the numerous options developed to remove pollutants, the most studied approaches are adsorption, catalytic degradation, and a combination of these two [6–9]. In the past few years, different types of 2D nanostructures such as graphene, graphyne, boron nitride (BN) nanosheets, tungsten chalcogenides, titanium carbide, and molybdenum disulfide have attracted considerable attention in the field of water treatment [10]. Graphene is a single atomically thick sp^2 hybridized carbon material that has extraordinary electrical, mechanical, optical, and thermal properties with a theoretical surface area of 2630 $m^2\ g^{-1}$ [11–13].

The aim of this article is to review the applications of graphene and graphene-based materials for the management of organic pollutants, especially in aqueous solutions. In Section 2, we provide insight into the possible mechanisms of graphene and graphene-based materials in the removal of organic molecules via adsorption and degradation. In Section 3, we review the performance of graphene and graphene-based materials for the adsorptive removal of organic pollutants. In Section 4, we discuss catalytic degradation of organic molecules by graphene and structures derived from graphene. In Sections 5 and 6, we describe the reusability and toxicity of these materials, respectively, which are important issues for environmental applications.

2. Management of organic pollutants

A huge quantity of pollutants is generated annually from industrial and household processes. These pollutants greatly affect the environment and human life, while their adverse effects tend to vary greatly depending on the structure of the pollutant [14]. Advances in nanotechnology are providing unprecedented opportunities to develop more efficient and environmentally tolerable platforms for the degradation of organic pollutants.

Of all nanomaterial-based platforms developed for the management of organic pollutants, graphene and graphene-based materials have been widely explored for the removal of organic pollutants [15–18]. The combination of graphene with many nanomaterials was also found to have synergistic effects for the removal of organic pollutants [19–22]. Graphene and graphene-supported materials can efficiently manage organic pollutants through two main pathways of adsorption and photodegradation. In accordance with the main goal of this review, we discuss detailed mechanisms of adsorption and photodegradation of organic pollutants in aquatic reservoirs.

2.1. Adsorption strategy for organic pollutants

2.1.1. Adsorption on graphene surfaces

Graphene is the superior carbon based adsorbent for adsorption of organic molecules. In comparison with other carbonic structures like activated carbon (AC) and carbon nanotubes (CNTs), graphene exhibited better adsorption capacities for organics [23]. A list of superior properties (e.g., hydrophobic nature, large surface area, and functionalization) of graphene allows them as better adsorbents than other counterparts [23,24]. The functionalized graphene showed preferable adsorption due to the large surface area (π-π