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Review

Adsorption of dyes by nanomaterials: Recent developments and adsorption mechanisms

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A B S T R A C T

Application of nanomaterials in dye wastewater treatment has received wide attention in recent years. This review highlights recent developments in the use of nanomaterials for the adsorption of dyes from wastewater. Specific adsorption mechanisms, improvements, particularly for increasing adsorption capacities, and toxicity are discussed for each nanomaterial. The accumulated data indicate that nanomaterials can be effectively used for treating dye wastewater. Nanochitosan, in particular, has a huge potential for commercial application due to its sustainability with respect to excellent adsorption performance, non-toxicity and low cost. Although the applications using nanomaterials have been developing rapidly, the technology is still far from achieving the ultimate goal of commercialization. Other considerations, such as regeneration methods and treatment of actual commercial textile dye wastewater, have not been sufficiently researched.

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1. Introduction

Dyes have been extensively used for thousands of years for textile, paint, pigment and many other applications [1]. Today, dyes play a critical role in textile, paint and pigment manufacturing industries, and at least 100,000 different dye types are commercially available currently [2]. To meet industrial demand, it is estimated that 1.6 million tons of dyes are produced annually, and 10–15% of this volume is discarded as wastewater [3]. As a result, dyes are major water pollutants. Excessive exposure to dye causes skin irritation, respiratory problems, and, for some dyes, increase cancer risk in humans [4]. In addition, the presence of dyes in wastewater also contributes to high chemical oxidation demand and causes foul odor [5]. Thus, it is of utmost importance to remove dyes from wastewater effectively to ensure safe discharge of treated liquid effluent into watercourses.

Typically, dye wastewater is treated using coagulation–flocculation [6], aerobic or anaerobic treatment [7], electrochemical treatment [8], membrane filtration [9] and adsorption methods [10]. Adsorption is the most popular of these methods, due to the effectiveness and the simplicity of the process. Dye manufacturing factories commonly use commercial activated carbon for dye removal, due to its high porosity and large surface area (500–2000 m^2/g) [11]. However, commercial activated carbon is relatively expensive because of high production cost [12]. Additionally, regeneration of activated carbon requires high-pressure stream, which contributes to the operation cost of this treatment system [13]. This high cost has motivated the search for alternative adsorbents that are both economical and efficient for dye removal.

Low-cost adsorbents derived from solid and agricultural wastes have received widespread attention from researchers in the last decade [14]. Most of these wastes have been shown to effectively remove dyes as well as heavy metals. For example, an adsorbent derived from palm oil waste removes copper [15] and zinc [16], as well as reactive dyes [17]. These potentially low-cost adsorbents have been intensively reviewed by Gupta [2]. However, most of the low-cost adsorbents are microparticles [18,19], and the small contact surface area requires considerable time to achieve maximum removal of pollutants. As most industries require a fast removal rate to sustain increasing pollutant capacities, developing these adsorbents for industrial applications is not feasible. Therefore, the need to develop sustainable adsorbents that are economical and offer both high removal rates and high adsorption capacities is urgent.

Nanomaterials, also referred to as nanoparticles, are particles that fall within the size range of 1–100 nm. Generally, well known nanomaterials are valued for their strength, highly active sites, low mass [20]. In addition to wastewater treatment, current research focuses on the development of nanomaterials for optical data storage [21], sensors [22] and durable and light construction materials. Although both nanomaterials and activated carbon have considerably high surface areas, some nanomaterials have two main advantages over activated carbon as adsorbents: they can be easily synthesized at a lower cost and smaller amounts are required for effective removal of pollutants [23]. Thus, it is expected that nanomaterials will become more economical than activated carbon for adsorption applications.

The adsorption capacities of different nanomaterials for various heavy metals have been reviewed intensively by Hua et al. [24]. As reviewed by these researchers, the heavy metals Cu(II), Ni(II) and Cr(VI) are easily adsorbed by ZnO, γ O_2O_3 and CeO, which exhibited adsorption capacities of 1600 mg/g, 171.1 mg/g and 121.15 mg/g, respectively [24]. These high adsorption capacities raise the expectation that these materials can be used effectively in wastewater treatment. In related research, the removal of different dyes using various nanomaterials has also shown promising results, recently which are discussed in this manuscript.

The aim of this present work is to discuss the application of different nano-materials for the adsorption of dyes. Although the different parameters related to adsorption, isotherm and kinetics are

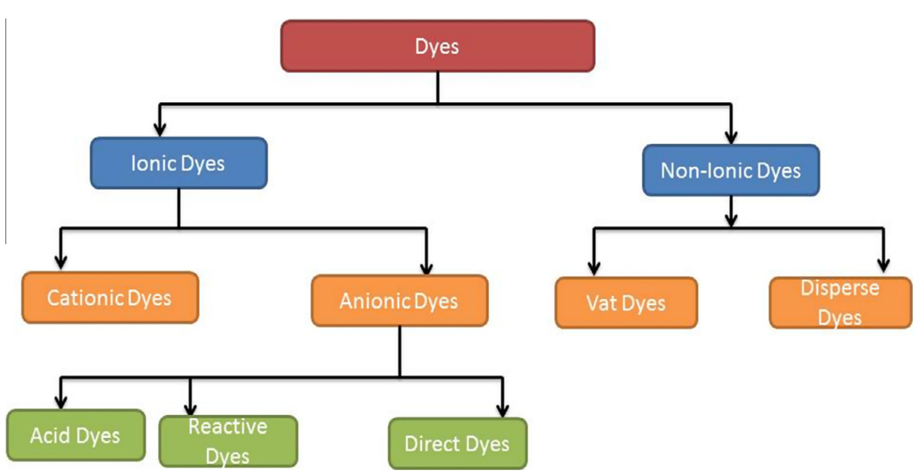

Fig. 1. Categorization of dyes according to ionic charge [3].