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Review

Dendrimers, mesoporous silicas and chitosan-based nanosorbents for the removal of heavy-metal ions: A review

E. Vunain*, AK Mishra*, BB Mamba

Nanotechnology and Water sustainability Research Unit, College of Science, Engineering and Technology, University of South Africa, Florida Campus, Johannesburg, South Africa

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ABSTRACT

The application of nanomaterials as nanosorbents in solving environmental problems such as the removal of heavy metals from wastewater has received a lot of attention due to their unique physical and chemical properties. These properties make them more superior and useful in various fields than traditional adsorbents. The present mini-review focuses on the use of nanomaterials such as dendrimers, mesoporous silicas and chitosan nanosorbents in the treatment of wastewater contaminated with toxic heavy-metal ions. Recent advances in the fabrication of these nanoscale materials and processes for the removal of heavy-metal ions from drinking water and wastewater are highlighted, and in some cases their advantages and limitations are given. These next-generation adsorbents have been found to perform very well in environmental remediation and control of heavy-metal ions in wastewater. The main objective of this review is to provide up-to-date information on the research and development in this particular field and to give an account of the applications, advantages and limitations of these particular nanosorbents in the treatment of aqueous solutions contaminated with heavy-metal ions.

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* Corresponding author.
E-mail addresses: evunain@gmail.com (E. Vunain), mishrak@unisa.ac.za (A. Mishra).

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1. Introduction

The term "nano" is derived from the Greek word for "dwarf". A nanometer (nm), from Greek "nanos" for "dwarf" is equal to one billionth of a meter or 10^{-9} of a meter. Nanotechnology is the art and science of manipulating matter (with at least one dimension size from 1 to 100 nm) at the atomic, molecular or supramolecular scale. At the nanoscale level, materials are characterized by different physical, chemical and biological properties than their normal size equivalent [1]. At nanoscale level, the surface area of particles increases with decreasing particles. Nanoscale particles (i.e., particles within the nanometer size–range) exhibit different mechanical, thermal, optical, electrical and magnetic properties from the properties exhibited by macroscopic particles [2–5]. At the nanoscale level, as the particle size decreases, the ratio of surface area to volume increases so much so that the surface properties become the dominant factor. For example at nanoscale level, materials such as polymers and ceramics, metals, metal oxides, carbon derivatives (carbon nanotubes and fullerenes) show a high ratio of surface area to particle size. This large surface area provides various unique properties that have widespread applications in a range of industries.

Nanotechnology has been useful in the manufacture of products and devices with dimensions in the nanosize range. Nanotechnology is sometimes referred to as a general purpose technology because it has a significant impact on almost all industries and all areas of society [6–12]. Nanotechnology focuses on the fabrication, characterisation and manipulation of substances at sizes in the nanoscale range of approximately between 1 and 100 nm. When materials have one or more dimensions less than 100 nm, the general rules of chemistry and physics no longer apply. As a result, these materials start to show unique and sometimes surprising properties. The rate of reactivity and their ability to conduct electricity increases drastically. For example, reduced to the nanoscale size, solids such as silver show increased anti-microbial properties, gold turns into liquid at room temperature, and inert materials like platinum and gold become catalysts, etc. Generally, materials with smaller particle size in combination with an increased surface area tend to exhibit unique and novel properties, thus creating a vast potential for a wide range of applications. Most importantly, the potential benefits of nanotechnology have already been identified by many researchers in areas such as health, agriculture, energy and water [9,10,13–16]. Nanotechnology offers leapfrogging opportunities in providing new technologies for the treatment of water and wastewater, and once fully utilised, is bound to make a major contribution to achieving the ultimate goal of clean water supply. One of the promising and well-developed environmental applications of nanotechnology has been in water and wastewater treatment where different nanomaterials are being utilised to help purify water through various mechanisms such as adsorption and sequestration of heavy-metal ions and other pollutants, removal and inactivation of pathogens, and finally the transformation of toxic materials into less toxic compounds [16–23].

1.1. Nanomaterials

Nanomaterials, also referred to as nanoparticles, are defined as materials within the size range of 1–100 nm. At the nano-range size, materials often possess novel size-dependent properties quite different from their bulk properties, with many of these properties such as high surface area, high reactivity, fast dissolution and strong sorption being used in water and wastewater treatment [18,24–31]. Nanomaterials have gradually developed an important role in solving water and wastewater problems because of their physical and chemical properties such as enhanced active sites, and abundant functional groups on their surfaces, high activity for adsorption and photocatalysis (high surface to volume ratio), and antimicrobial properties for disinfection. Furthermore, magnetism or other unique optical and electrical properties also make these materials excellent candidates for wastewater treatment [16,32,33]. In addition to water treatment, current research focuses on the development of nanomaterials in other fields such as cosmetics and personal care items, electronics, pharmaceuticals, transport, construction, medicine, agriculture, energy, and sensors, just to name a few [34–37]. Other applications of nanomaterials make use of their discontinuous properties such as superparamagnetism, quantum confinement effect, etc. Nanomaterials have been produced in different shapes and sizes, integrated with a wide range of components and functionalised with a wide range of active components for various applications. For instance, nanomaterials have been incorporated in nanostructured catalytic membranes for application in water treatment. Generally, nanomaterials can be classified as carbon and non-carbon materials as shown in Fig. 1 [38]. Carbon-based materials include carbon nanotubes and graphene while the non-carbon materials are inorganic nanomaterials based on metal, metal oxides and quantum dots. However, nanomaterials made of a combination of different materials are currently being developed [39].

Nanomaterials find application in water treatment, which is to reduce concentrations of toxic components (e.g., metal ions, organic and inorganic compounds, radionuclides, as well as bacteria and viruses) to microliter per liter (μL/L) levels [40].

1.2. Nanomaterials as adsorbents

For an excellent adsorbent to remove a large amount of pollutant in a short period of time, it should possess a high surface area, fast adsorption rates and short adsorption equilibrium times. Nanomaterials have been used as nanosorbents due to their high adsorption capabilities because of their large surface areas, i.e., surface area per unit mass and specific functionalities. In addition, nanosorbents can be transported effectively in pore media because they are smaller than the relevant pore spaces and as such they tend to be highly mobile in such media. In their application in water treatment, these sorbents can be employed in situ, within the contaminated zone where treatment is required. Their ability to remove pollutants from subsurface and other environments that are very difficult to access in situ and doing so rapidly and effectively within reasonable costs is the ultimate goal [40–47]. Nanosorbents employed as separation media in water purification to remove inorganic and organic pollutants from contaminated water are nanomaterials, including nanoparticles. The potential of nanomaterials as adsorbents in water treatment cannot be overemphasized. The literature review indicates that much research has been published with the main goal of investigating the removal of pollutants (either in gas or liquid medium) from water and wastewater using nanomaterials as sorbent materials [47–58].

1.3. Objective of this review

The purpose of this paper is to discuss the application of different nanosorbents for the removal of heavy-metal ions from water and wastewater. The primary focus of this review is on nanomaterials such as dendrimers, mesoporous silica materials and chitosan nanomaterials which are currently used in environmental remediation and particularly in the removal of heavy-metal ions from water and wastewater. Different parameters related to adsorption isotherms and kinetics are reported. It is our hope that this review will provide a clearer view and will inspire ideas for the development of next-generation nanomaterials for the removal of heavy-metal ions from water and wastewater. We also trust that the information contained in this review will assist in speeding

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