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REVIEW ARTICLE

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Advances in Nanotechnology for Wastewater Treatment and Water Reuse: A Review

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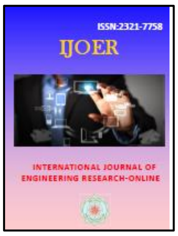

Abstract

Water scarcity, driven by population growth, pollution, and climate change, is one of the most pressing global challenges. Conventional water treatment technologies such as disinfection, decontamination, and desalination are effective but energy-intensive, costly, and chemically demanding. In this context, nanotechnology has emerged as a promising alternative for enhancing water treatment efficiency and sustainability. Nanomaterials such as carbon nanotubes, graphene oxide, titanium dioxide, silver nanoparticles, and zeolites have demonstrated superior performance in filtration, catalysis, photocatalysis, and disinfection. These materials enable the development of advanced membranes with higher permeability, selectivity, and resistance to extreme conditions, while also supporting innovative processes like forward osmosis and integrated nutrient recovery. Despite challenges related to cost, scalability, and potential ecotoxicity, nanotechnology offers a transformative pathway for wastewater treatment and water reuse. This review highlights recent developments, applications, and limitations of nanomaterials in water purification, emphasizing their role in achieving sustainable water management.

Keywords: Nanotechnology, wastewater treatment, nanomaterials, nanofiltration membranes, photocatalysis, water reuse, disinfection, water scarcity.

Introduction

Water scarcity and treatment. Water scarcity problems are rapidly increasing due to population growth, pollution, and climate change (Franek et al. 2015).

In the coming decades, water scarcity will be the watchword driving actions ranging from selling water to the population to war, unless new ways of providing clean water are found (Neira-Fernández 2009). Although water disinfection, decontamination, and desalination methods can mitigate some of these problems, these treatment methods are generally chemical and energy-intensive, requiring significant investment and engineering expertise (Shannon et al . 2008).

On the other hand, the use of alternative water sources, such as rainwater and treated wastewater, is one of the most promising options for integrated water management (Arnold et al .

2004). The greatest concerns regarding water safety in this form of exploitation are related to the microbiological and chemical contaminants found in wastewater, among which endocrine disruptors and pharmaceuticals are recognized as priority pollutants due to their ubiquity and ability to affect aquatic organisms, even at certain concentrations (Gil et al. 2012). In this context, the development of new water treatment technologies is urgently needed to meet water quality requirements for reuse and to ensure environmental protection.

Nanotechnology in wastewater decontamination processes. The emerging problems of environmental pollution worldwide require continuous innovation in techniques for the remediation and treatment of our natural resources. Without a doubt, one of the most fragile is water.

Nanotechnology is a potential solution for long-term water conservation, with techniques such as filtration, the use of nanoparticles in catalysis, and desalination. Furthermore, with the development of nanotechnology, conventional techniques used in water treatment, such as adsorption, flocculation, and coagulation, can be enhanced (Lu & Astruc 2018). Nanotechnology has been effectively used in the past for groundwater remediation, bioremediation, ink removal, and filtration processes (Tyagi et al. 2018). Therefore, nanotechnology is effective in addressing water-related problems, as the use of nanomaterials favors the development of more efficient and advanced water treatments.

Hence the importance of knowing the latest developments in nanotechnology and nanomaterials with a focus on the potential and limitations for their application in wastewater treatment to improve effluent quality and for water reuse (Obare & Meyer 2004).

The objective of this review is to provide an overview of advances in nanotechnology in wastewater treatment, paying particular attention to the use of nanomaterials in the manufacture of filtration membranes and the use of nanoparticles for catalysis and photocatalysis.

Nanotechnology Basics. Nanotechnology involves the manipulation of materials at a near-atomic scale to produce new structures, artifacts, and materials. Nanoparticles are particles with dimensions in the range of 1–100 nm (Morose 2010). Therefore, nanoparticles can be effectively transported by groundwater flow (Zhang 2003).

Atoms and chemical bonds range in size from a few tens of nanometers, with the smallest structures measuring a few nanometers (Chaturvedi 2012). This is because as soon as a few atoms are close together, the resulting structure is only a few nanometers in size.

There are two approaches used in nanotechnology. Construction (bottom-up), where materials and artifacts are built from molecular components that are chemically assembled using molecular recognition principles (budding, reverse micelle, enzyme-substrate interaction, and biomimetic principles). Destruction (top-down), where nano-objects are constructed from larger entities without control at the atomic level (nanolithography, chemical etching, etc.). Nanoparticles are formed as a result of supersaturation of soluble phases when a solubility change occurs (Simeonidis et al . 2016).

The science of interfaces and colloids has undergone significant development, leading to the emergence of several materials that can be used in nanotechnology, including carbon nanotubes and other fullerenes, various metals, metal oxides, nanotubes, and dendrimers.

The properties of nanomaterials can be consistently different from those exhibited on a macroscopic scale due to increased surface area, volume ratio, and quantum effects. These factors can alter reactivity, catalytic properties, mechanical strength, and electrical characteristics (Chaturvedi et al . 2012). Thus, opaque substances become transparent (copper); stable materials become combustible (aluminum); solids become liquid at room temperature and increase their catalytic activity (gold); and insulators become conductors (silicon).

The new properties of nanomaterials promise to provide new technology and nanotechnology is already being used in hundreds of products in various industries, with fairly rapid growth expanding the market (Morose 2010).

Membrane filtration materials . Nanotechnology could bring revolutionary advances to the water desalination industry, although the development of such membranes is still in its early stages and several challenges remain (Lee et al. 2011). The main challenges are the high cost of nanostructured materials and the difficulty in scaling up membrane manufacturing processes for commercial use.

According to Lange (2010), there are three technologies that promise to reduce desalination requirements by up to 30%: Osmosis (direct and reverse), membrane composites made with carbon nanotubes, biomimetic membranes.

Currently, there are several membranes developed with nanotechnology (Table 1) (Zhu et al. 2012). Nanotechnology offers a wider range of solutions for new membrane materials (Lee et al. 2011, Ng et al. 2010), including: graphene oxide membranes (Abraham et al . 2017), ceramic nanofiltration membranes, magnetic nanoparticles (Jung et al . 2004), anti-leakage coated polymeric membranes (organic brush-like coatings, nanoparticle-impregnated membranes), membrane composites (thin film reverse osmosis membrane composites, combinations: metal/metal oxides + polymer, carbon nanotubes + polymer, zeolites + polymer and aquaporin (AQP) + polymer).

Table 1. Membrane technologies based on nanotechnology developed worldwide (Zhu et al., 2012)

No	Organization	Country	Type of Technology
1	Banaras Hindu University	India	Containers with filters based on carbon nanotubes to remove contaminants
2	Argonida	United States	Aluminum oxide nanofiber filters developed on glass fiber substrate
3	Rensselaer Polytechnic Institute	United States	Equipment with carbon nanotube filters for contaminant removal
4	SolmeteX	United States	Resins that bind heavy metals for the removal of mercury, arsenic, cyanide, and cadmium from water
5	North-West University, Potchefstroom	South Africa	Nanofiltration technology through nanomembranes
6	Filmetc Corporation	United States	Nanofiltration technology through nanomembranes
7	Stephen & Nancy Grand Water Research Institute	Israel	Reverse osmosis
8	Long Beach Water Department	United States	Two-stage filtration process at relatively low pressure
9	Institute of Polymer Science, Stellenbosch University	South Africa	Nanofiltration technology through nanomembranes

On the other hand, graphene membranes have excellent permeability properties, and scientists in Manchester recently demonstrated that it is possible to control the interlayer to make it selectively permeable, thus enabling its use in desalination processes, achieving up to 97% NaCl removal (Abraham et al . 2017). However, their cost is not sustainable for large-scale wastewater treatment. Ceramic membranes offer very high resistance to extreme operating conditions (pH, temperature, flow rate, flushing intensity) and to the presence of oxidizing agents and ultraviolet light. Their surface can be modified with photocatalytic oxides and organic coating agents (for disinfection and overflow reduction).

Silver and titanium nanoparticles are ideal for membrane incorporation and thus reduce leakage in polymeric membranes (Ng et al. 2010). Zeolite, carbon nanotubes, and AQP provide high permeability.

Although the increased permeability of zeolite thin-film membrane nanocomposites is lower compared to CNTs and AQPs, their adaptability to commercial use is easier and faster due to their similarity to currently commercially available reverse osmosis membranes (Lee et al. 2011). On the other hand, several challenges remain in the production of CNT-AQP-based membrane composites. In CNT membrane composites, improvements in salt rejection functionalization and preparation of aligned nanotube arrays are required. In AQP-based membrane composites, the rejection layer is formed by aquaporin proteins incorporated and immobilized on an ultrathin amphiphilic polymer layer to mimic the natural cell membrane. A porous support layer is added on one or both sides for mechanical support. Several practical problems need to be addressed in developing AQP-composites, such as identifying suitable support materials and optimizing AQP production and incorporation. Furthermore, the costs, specific rejection, and long-term operational stability of this type of membrane are still unknown (Lee et al. 2011, Subramani et al. 2011).

The introduction of these new materials is beginning to spark renewed interest in osmosis. In this desalination process, a rinse solution is used to extract fresh water from treated saltwater or wastewater (based on the osmotic pressure difference rather than the imposed hydraulic pressure), then low-grade thermal energy is used to reconcentrate the diluted rinse solution and recover the fresh water (Cath et al . 2006). Specific membranes need to be designed for forward osmosis applications, and some products are already commercially available (Hydration Technology Innovation, Albany, USA).

Other innovative processes for wastewater treatment are includes: i) The use of forward osmosis for desalination of treated effluents (Cath et al. 2010), ii) Forward osmosis in a membrane bioreactor (Achilli et al. 2009), iii) Nutrient recovery from treated effluents with an integrated system of microfiltration, nanofiltration and reverse osmosis (Mrayed et al. 2011).

Nanomaterials for catalysis and photocatalysis. Nanomaterials are more effective than conventional catalysts for two reasons: their extremely small size (between 80-100 nm, with the consequent higher surface area-to-volume ratio) and their higher reactivity related to the nanoscale itself (Chaturvedy et al. 2012). The latter aspect (e.g., understanding how decreasing the size of the catalytic particles alters the intrinsic catalytic performance beyond simply an expansion of the surface area), and the design/preparation of catalysts with a more effective size and structure are objectives of catalysis research.

Heterogeneous catalysis in particular has the potential to be one of the most important and productive areas of nanoscience and technology in the coming decades (Shannon et al . 2008).

In wastewater treatment, the use of advanced oxidative processes for the removal of resistant organic micropollutants has been extensively studied, but the adoption of UV lamps and ozone makes the energy expenditure prohibitive. The application of photocatalytic solar processes based on recently developed nanomaterials may open up opportunities for the development of low-cost integrated processes that achieve the high quality required for the reuse of rainwater and wastewater.

A high number of nanomaterials have been proposed for photocatalytic applications, however common limitations have been found for either the materials or the process: i) Charge recombination (with consequent reduction of light efficiency), ii) Visible light transparency (although a strong effort has been concentrated on doping of catalysts), iii) Colloidal instability and spillover (potential occurrence and extent in real matrix is mostly unknown), iv) Catalyst recovery (in case of bed reactors), v) Low activity, light spreading (in case of supported catalysts).

Among semiconductor catalysts, titanium dioxide (TiO 2) has received the greatest interest in R&D of photocatalysis technology (Chong et al. 2010). Although TiO 2 -based photocatalysis is widely studied and the successful removal of a wide range of organic molecules has been demonstrated, its application has not yet reached commercialization mainly due to difficulties in catalyst separation and recovery and its transparency to visible light.

The proposed approaches to overcome post-separation problems are: i) Use of filtration membranes (Doll & Frimmel 2005). ii) Preparation of the catalyst in nanoscale fibrils (e.g., nanotubes, nanorods, nanofibers, and nanowires), where the dimension is in the mm range, allowing easy post-separation for the establishment of conventional filtration (Chong et al . 2010, Huang et al. 2011). iii) Preparation of catalysts on supports and nanocomposite materials, e.g., glass-supported photocatalyst, zeolites, ceramics, activated carbon (Chong et al. 2010, Zhang et al. 2009). In most cases, both act as adsorbent and photocatalyst.

To improve visible light adsorption and develop solar photocatalytic processes, doping with heavy metals and non-metals has been widely investigated during the last decade (Han et al. 2009), among which nitrogen doping seems to be more promising.

In general, there are few studies available that address the problem of colloidal instability, due to salinity and the presence of humic substances or other dissolved organic and inorganic compounds that can be found in water bodies and effluents (Laera et al. 2011).

Furthermore, in applications involving natural water and treated effluents, influent turbidity is a limiting factor for any photocatalytic process. Water with less than 5 NTU is suggested to be suitable for photocatalytic degradation, while 30 NTU is the limit for water disinfection (Chong et al. 2010). The use of sonication instead of UV light has recently been proposed to overcome the turbidity problem in water and wastewater applications (Pang et al. 2011).

An interesting preparation of TiO 2 nanotubes (Okour et al. 2010, Shon et al. 2009), which starts from sludge obtained during flocculation of municipal biological wastewater treatment effluent with titanium salts, after drying and incineration, where it was observed that the thio-urea doped nanotubes showed high photocatalytic activity.

Other nanoscale photocatalysts are those based on zinc oxide (Chiu et al. 2010), since this material is cheap and the active catalyst can be easily prepared under mild conditions forming nanofibers and nanorods.

Nanomaterials for water disinfection . According to Li et al. (2008), several nanomaterials (natural and manufactured) have been shown to have strong antimicrobial properties including: chitosan, silver nanoparticles (nAg), photocatalytic TiO 2 , fullerol, aqueous fullerene nanoparticles (nC60), carbon nanotubes (CNTs). Since these antimicrobial nanomaterials are not strong oxidants and are relatively inert in water, they are not expected to produce harmful disinfection by their co-products. Therefore, they have the potential to replace or enhance conventional disinfection methods, if appropriately incorporated into conventional treatment processes and decentralized point-of-use and reuse treatment systems.

There are several proposed mechanisms, although in most cases their effective action is still being investigated. The action of photocatalytic nanoparticles usually involves the production of hydroxyl radicals, while other materials appear to cause direct damage to the cell membrane and/or interfere with metabolic processes.

The main limitations identified for the application of these nanomaterials in water and wastewater disinfection are:

- Disinfection processes that require the catalyst to be in contact with the cell membrane surface for microbial inactivation must be successful. i) Catalyst recovery is difficult. ii) There is no residual antimicrobial action in the water.

Promising applications of nanomaterials for water disinfection are being developed for catalyst support in filters, providing self-cleaning filtration that can be used in point-of-use applications.

Potential ecotoxicity of nanomaterials and related processes in water applications . Nanomaterials in water do not directly affect humans, but there is a possibility that nanomaterials may be ingested when consuming fish. Therefore, the impact of nanomaterials on aquatic organisms must be taken into account. The harmful effects of nanomaterials on aquatic organisms are primarily related to nanoparticles.

The emission of nanoparticles into the environment can come from point sources, e.g.: landfills or treatment plants, or from non-point sources, such as washing machines, clothing or any other material containing nanoparticles (Gehrke et al . 2015).

An extensive look at the various effects of TiO 2 nanoparticles was provided in a 2010 case study published by the United States Environmental Protection Agency (EPA) (Pederson et al. 2011). In that study, different types of TiO 2 nanoparticles, different entry pathways, and different effects on the environment and on organisms, including bacteria, algae, invertebrates, fish, and plants, were reported. Reported effects on aquatic organisms include decreased Daphnia reproduction as well as respiratory distress, pathological changes in the gills and gut, and behavioral changes in fish. Various acute effects on algae could be demonstrated depending on the mean effective concentration, primarily dependent on particle size.

Conclusions

Nanotechnology is a field with great potential. Continuous improvements are being made in filtration systems using membranes that not only decrease in size but also in selectivity and durability. Although the cost remains high for large-scale water treatment, it is important to stay abreast of advances and try to replicate successful experiences from other countries in our own community. Monitoring improvements in desalination processes could be used in the future, for example, in the desalination of Lake Titicaca, thereby obtaining a source of water for the region's residents. On the other hand, in populations with limited access to water, it is not enough to simply implement water harvesting devices; it is also necessary to ensure that this water is of good quality and suitable for consumption, which is achieved through catalytic and photocatalytic processes using nanoparticles.

The field of nanotechnology has not yet been fully explored in our country, but it is important to know that many techniques can be adapted to our needs, provided we find strategic partners.

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