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Applications of Nanotechnology in Water and Wastewater Treatment: A Review

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Abstract: Water pollution due to heavy metals, organic and inorganic matters and biological organisms is a matter of serious concern all around the globe. Thus, providing clean and safe drinking water at a reasonable cost has become a challenge nowadays. Therefore the importance of technological advancement to facilitate integrated water management cannot be overruled. Due to this, emergence of nanotechnology has delivered pioneering solution to problems in the field of medicine, engineering, physics, chemistry, etc. Nanotechnology is basically the world of science employing nanoparticle for various engineering applications including environmental remediation. Among the nano-based techniques, use of nanoadsorbents, nanomembranes, and nano-photocatalysts has been quite promising in water and wastewater treatment, at both small and commercial scale. Nanoparticles have a higher aspect ratio, larger pore-volume, electrostatics, a higher specific surface area which is quite useful in processes like sorption, catalysis, censoring in the field of water treatment having higher efficiency, flexibility, being multifunctional and affordability. Considering these aspects, nanotechnology has proved to be an innovative, eco-friendly and an advanced treatment technique. The main limitation in applying nanotechnology is that uptil now most of the researches are confined to laboratory or pilot scale only. In this review, we have discussed in brief about a few recently used nanomaterials that are presently employed in treating water, with a focus on nano-based adsorbents and filtration membranes.

Key words: Nanotechnology, heavy metals, water treatment, nano filtration, nanoadsorbent.

Introduction

Worldwide, growing demand of water has worsened due to population growth, climate change, and degrading quality of water. Providing clean and affordable water is the utmost need of this century. As per report of W.H.O. 2012, more than 780 million people face shortage of safe and clean drinkable water. Due to increasing population, industrialization and economic boom worldwide, demand of water has increased many folds (Khan et al., 2015). It is essential to treat water especially in affected areas where treatment facilities are lacking or doesn't exist.

Current water and wastewater techniques have their limitations in terms of water quality as per the stringent water regulations. These conventional treatment techniques have one or the other limitations (some are listed in Table 1) (Das et al., 2014). In order

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Table 1: Conventional treatment techniques and their limitations

S. No.	*Type of treatment*	*Limitations*
1.	Distillation	High requirement of energy, water. Pollutant boiling point >100°C difficult to remove.
2.	Biological treatment	Microorganisms difficult to control and by-product damages cells, not cost effective and is time taking.
3.	Ultraviolet treatment	Expensive method and inactivated due to turbidity, Ineffective due to heavy metals and ineffective in inorganic contaminants removal.
4.	Ultrafiltration	Not remove dissolved inorganics, high energy requirement, difficult in cleaning.
5.	Chemical transformation	Excess reagents needed, low-quality mixture, Inactive adverse conditions, selective method.
6.	Coagulation and flocculation	Low efficiency and pH dependent.

to understand and solve this crisis of water quality, new technologies and sustainable methods are needed to be developed. Due to higher treatment efficiency, nanotechnology emerges as a promising technology, thereby enabling cost effectiveness with certain limitations and as an acceptable treatment technique. The involvement of nanotechnology in treatment has envisaged us with high performance, affordable wastewater treatment and ending the reliability on infrastructures (Qu et al., 2013). Nanotechnology not only enabled to overcome the limitation of conventional treatment technologies but is also providing sustainable and economic utilization of available sources.

Nanoparticles exhibit unique properties such as high sp. surface area, reactivity towards pollutants, high functionalization, adsorbing properties etc. in waste or wastewater treatment (Theron et al., 2008). At the nano-size level, materials are characterized by different properties which are generally enhanced as compared to their respective standard size counterparts. For instance, at the nano-scale level the ratio of surface area to particle size is quite high. By employing nanocomposite filters and membranes and other properties improves the efficiency as well as life of treatment systems. Treatment using nanotechnology for contaminants like metals, ions, organic as well as inorganic, pathogenic substances has vast scope.

Nanotechnology-facilitated water and wastewater treatment guarantees to not solely overcome major challenges featured by existing treatment technologies; however conjointly improves treatment capabilities that might permit economic use of unconventional water treatment techniques to expand and make full usage of the available water sources. Nano-materials have a high ratio of surface to volume that results in good interaction with pollutants and/or microorganism (Theron et al., 2008). Nanotechnology takes these existing treatment processes to new heights. Nano-material dimensions are measured generally within one hundred nm in dimension and contain materials with the high surface area and considerably modified properties (Pillay et al., 2009). Thus nanotechnology has provided tremendous opportunities in water treatment field along with sustainability (Diasa et al., 2007).

The nano shape enables unique physico-chemical properties like large surface area and high specific affinity. This property has shown higher removal of organics, inorganics involving heavy metal removal from wastewater. The growing interest and in depth exploration in nanotechnology has aided in synthesis and development of new nanoparticles and binary composites involving magnetic nanoparticles, carbon nanotubes, titanium based nanoparticles, metal and Fe based nano-composites and activated carbon (Ponder et al., 2000). A few commonly used nano-adsorbents for water and wastewater treatment along with their specific properties are shown in Table 2 (Xiaolei et al., 2013). The main advantages of them are high adsorption capacity and superior efficiency, their high reusability, synthesis at room temperatures, super magnetism, quantum confinement effect as well as eco-toxicity. This review will focus on the applicability of different nanoscale materials and their uses in treating wastewater polluted by organic and inorganic compounds, heavy metals, bacteria and viruses. Moreover, the use of various nanoadsorbents and nano-based filtration membranes is also examined.

Table 2: Commonly used nano-adsorbents for water and wastewater treatment, their specific properties and applications

S. No.	*Nano particle*	*Properties of nano-particle*	*Technology use*
1.	Carbon-based nanotubes	Large specific surface area, high adsorption sites, contaminant interactions, changeable surface chemistry, easy reuse.	Contaminant preconcentration/ detection, adsorption of recalcitrant contaminants.
2.	Nano-Ag	A wide range of antimicrobial activity capacity, less harmful to humans	Anti-biofouling membranes
3.	Nano-magnetite	Can change surface chemistry, superparamagnetic	Forward osmosis
4.	Nano-TiO_2	Photocatalytic behaviour with UV and visible light, less harmful to humans, Stable, economical	Photocatalytic reactors, solar disinfection systems
5.	Derivatives of Fullerene	Photocatalytic activity in the solar spectrum, high selectivity	Photocatalytic reactors, disinfection systems

Role of Nano-materials in Industrial Wastewater Treatment

Conventional adopted treatment techniques for water pollutants include reverse osmosis, coagulation-flocculation and filtration which are generally not efficient in removing all the target pollutants effectively. Therefore, there is a need for resilient techniques and membranes to be used in water treatment and its purification.

With the aim of refining the conventional treatment processes, the applicability of nanomaterial was explored to devise separating media of high superiority in terms of reactivity and output (Bellona et al., 2007). Nanofiltration has been incorporated at several treatment plants to yield effluent having low concentrations of pollutants (Bruggen et al., 2008). In addition, the use of nanomaterials in disinfecting water and bio-remediating wastewater has gained recognition (Hu et al., 2005; Mohan et al., 2007). For example, nanomaterials like TiO_2 are among the favourable nanocatalysts that were tried for antimicrobial action and proved quite effective.

Few other developments in nanotechnology applications include: nanofiltration of biologically treated wastewater from the paper and pulp production plants (Manttari et al., 2006); the degradation of organic dyes by ZnO nanoparticles (Ullah et al., 2008); and treatment of effluent from molasses distillery using nano-membranes (Satyawali et al., 2008).

Nano-based Adsorbents

Adsorption has become one of the surrogative method of treatment, nowadays, as the search for low-cost adsorbents possessing higher metal-binding capacities has aggravated (Leung et al., 2000). Nano-sized materials for removal of heavy metal ions should have certain distinctive properties like, reasonable cost, higher metal adsorption ability and the capability to switch over high valence ions to low valence or zero valence ions, thus lowering toxicity. The materials showing these characteristics include nano-iron based oxides, silicates and porous zeolites. In some of the recent studies, binary nano-sized iron based oxide nanoparticles were synthesized and successfully applied to remove hexavalent chromium, arsenic and lead from water at low pH (Khan et al., 2016; Zhang et al., 2013; Khan et al., 2017).

Many types of materials are nowadays used as sorption sites in nano-particles and act as separation media for arresting heavy metals like Cd^{2+} using nitric acid, hydrogen peroxide, etc. (Li et al., 2003). These are oxidized in order to generate high adsorption capacity towards metal ions and have faster kinetics in associate with many functional groups like hydroxyl, and carbonyls (Vukovic et al., 2010). The oxidized nanotube had shown higher efficiency when pH is well above the isoelectric point (Lau et al., 2015). Many of them are used for effective removal of Cu^{2+}, Pb^{2+}, Cd^{2+}, and Zn^{2+} also.

Many studies are available in literature for applicability of nano-adsorbents in removing of toxic elements like As, Cr, Cu, Pb and Ni in ionic forms (Qi et al., 2014). Magnetite nanorods are extensively used for removal of Fe^{2+}, Pb^{2+}, Cd^{2+}, and Cu^{2+}. It was also observed in some cases that nanorods show better adsorption capacity in comparison to nanotubes, for example in case of Zn^{+2} and Pb^{+2} removal but lower in case of Cu^{+2}. Some other types are also available such as super-paramagnetic nanoparticle having faster and selective adsorption towards Hg^{+2} (Shipley et al., 2013). In the study of nanohematite it was observed that surface having hydroxyl group, allows the adsorption of heavy metals ions and proves that the adsorption of Pb^{+2} and Cd^{+2} is endothermic, while Zn^{+2} is exothermic (Tu et al., 2012).

Although, having very high adsorption capacities, they have certain limitation also like high production cost, technical hurdles, toxicity of carbon nanotubes, difficulty in bulk volume production, etc. A generalized schematic diagram for nano-adsorption mechanism is depicted in Figure 1(a).

Nano-based Membranes

Membrane filtration has a noteworthy role to play in remediating water from various pollutants. In the last decade, the development of ceramic and polymeric membranes has positively affected on the use of membranes. However, fouling of membrane is a major problem in the filtration process that poses a grave concern challenging the feasibility of membrane use. Nanotechnology is quite useful in the fabrication of water purifying membranes. In a recent study, production of water filtration nanostructured membranes using nanomaterials like carbon nanotubes and nanoreactive membranes was reported (Theron et al., 2008). In another study, an approach to enhance membrane efficiency, while mitigating fouling, was carried out by structuring the membrane surfaces at the nano and molecular scale (Cohen et al., 2006). The structural management of nanofiltration membranes to make a surface with salt rejection selectivity was attained (Linder et al., 2006). In a somewhat parallel approach, the nanostructure surface alteration of microporous ceramics was attained by for efficient virus separation (Wegmann et al., 2008). The method involved coating the internal surface area with a colloidal nano-dispersion of hydrated yttrium oxide. Further, it was thermally treated to attain an electropositive Y_2O_3 coated surface. The altered nanostructure filters were successful in removing 99.9% of 25 nanometre dia MS2 bacteriophages from feeded water having pH 5 to 9.

Moreover, membranes for water treatment made up of nano-reactive material are synthesized. These membranes decompose pollutants such as 4-nitrophenol (Dotzauer et al., 2006) and bind metal ions (Hollman et al., 2004) in aqueous solution. Polysulfonate UF membranes loaded with silver nanoparticles proved to be effective against *E. coli* K12 and *P. mendocina* bacteria strains and exhibited noteworthy enhancement in removing virus (Zodrow et al., 2009).

Simultaneous filteration of organic contaminants along with photocatalytic oxidation was achieved by fabricating TiO_2 nanowire membranes (Xiao et al., 2008). In another study, TiO_2/Al_2O_3 composite membranes were devised using extrusion technique and sol–gel/slip casting technique, proved successful in decomposing Direct Black168 dye (Zhang et al., 2006).

Application of nanotechnology based membrane filters will further gain acceptance in future, due to their high efficiency in removing inorganic, organic and biological impurities, with metal selectivity as well as, being durable, low cost and resistant to fouling. A generalized schematic diagram for nano-membrane filtration that retains the specific pollutants is illustrated in Figure 1(b).

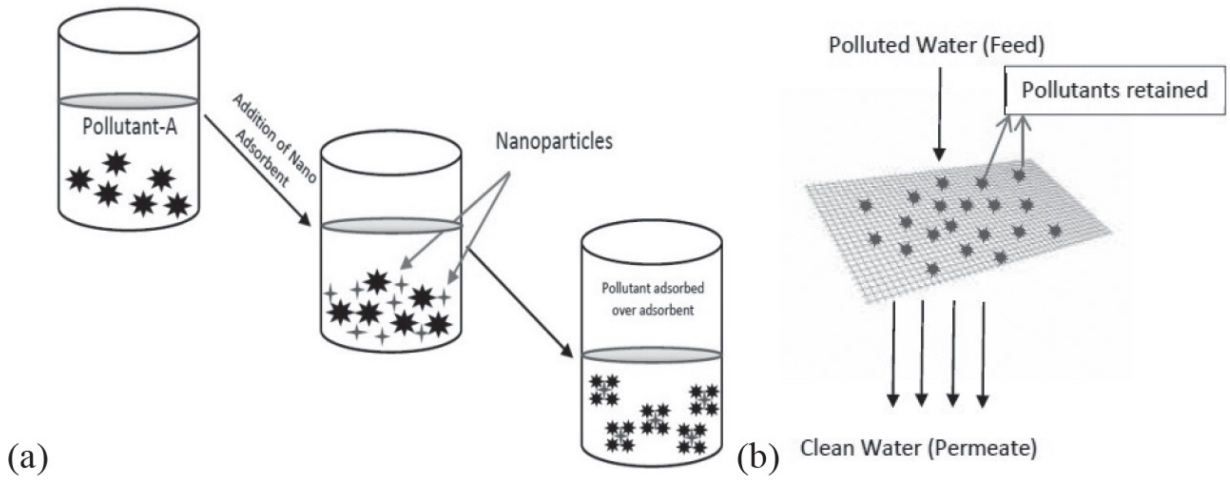

Figure 1: (a) Mechanism showing Nano-adsorption and (b) Nano-membrane filtration.

Critical Assessment and Conclusion

Water scarcity and its deteriorating quality have set the alarms ringing as a present and future threat to human race and its existence on earth. As a consequence, water treatment technologies are gaining consideration globally. The increasing trends of ongoing research including those incorporated above have made it clear that nanotechnology holds a huge potential which seems to be established into a very powerful water treatment tool of the 21st century. Nanotechnology may simply combine with conventional technologies and modify, endorse or clarify these prevailing scientific ideas. Although the future seems quite progressive but it needs collaborative effort from different fields in order to get speedy, economical, and complete removal of target pollutants. However, supplementary studies are still needed to address the challenges posed by nano-based materials. Up till now, only a few nano-materials have been developed commercially, although their low production cost is of paramount importance for their extensive applications in water treatment. However, treatment of wastewater involving nanotechnology so far have mostly been studied at lab and pilot scale only, perhaps due to financial reasons. Although most of the nanomaterials included in this review are investigated at lab scale, fewer are studied at pilot scale or even commercialized. Among the various nano-based materials and membranes discussed in this review, these nanotechnology aided membranes exhibited higher potential even at full scale application. Therefore, these are also commercialized for treatment of water. Besides, with the increasing use and wide applicability of nanomaterials, curiosity regarding issues of the potential toxicity caused to the environment and human well-being have also arisen. So it is important to make sure that nanomaterial is safer to apply, while harnessing their full potential. Notwithstanding these information gaps, new research should include concerns regarding potential threats to human well-being and our ecosystem. In addition, procedures and guidelines on detrimental properties and exposure of nanosized materials should be taken care of.

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