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Review Article

NANOTECHNOLOGY IN DRINKING WATER PURIFICATION: A CRITICAL REVIEW

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Abstract: With rapidly growing economy and burgeoning population, the global water resources are seriously affected by pollution. However, for providing safe drinking water to people, novel innovative technology that can ensure total quality of drinking water is required. Nanotechnology emerges as a revolutionary technology that can helps to address key needs related to energy and environment. The environmental fate and toxicity of a nanomaterial is one of the major drawbacks of nanotechnology in using for water purification. To overcome these drawbacks, the novel nanotechnologies have been developed in recent years. In this article, an overview of advances in nanotechnology for water treatment processes is mentioned, including nanobased materials such as, nanoadsorbents, nanometals, nanomembranes, photocatalysts and some other novel techniques.

Key words: Nanotechnology; Water purification

INTRODUCTION

Nanotechnology is the engineering and art of manipulating matter at the nanoscale (1-100 nm). Currently, several nanomaterials are under active research and development because nanotechnology offers a potential and novel approach in the treatment of surface water and groundwater [1]. Recent advances in nano engineered materials for water treatment provides nanoadsorbants, nanometals, nanomembranes, photocatalysts, bioactive nanoparticles and nanoparticles enhanced filtration, most of which are compatible with existing technologies, and can be integrated into the conventional methods [2]. Nanotechnology and engineered nanomaterials allow efficient removing the water contaminants such as inorganic heavy metals, organic contaminants and microorganisms [3]. Diallo et al. [4], Cloete et al. [1] and Hotze and Lowry [5], in their respective studies revealed that, nanotechnology has great importance in the field of desalination, water recycling and water reuse along with sensing and detection of water quality. In recent years, research in the field of nanotechnology has grown exponentially as scientists and engineers continue to develop nanomaterials with unique properties. The applications of nanotechnology have been recommended for meeting the needs of poor people in effectively removing contaminants from water that have been proven challenging in conventional water treatment technologies [6].

The potential impact areas for nanotechnology in water applications are divided into three categories which are treatment and remediation, sensing and detection and pollution prevention indicating that, nanotechnology has wide range of application in the field of drinking water treatment [1]. The two major categories of technologies extensively used in both the conventional method as well as the nanotechnology are adsorption versus reactive and *in situ* versus *ex situ*. Adsorption removes contaminants by sequestration whereas reactive technologies take parts in the degradation of contaminants [7]. *In situ* technology involves treatment of contaminants at the site itself whereas, *ex situ* refers to treatment away from the site or transfer of the contaminant to more convenient location for treatment [8].

Small scale purification: Nano structured materials has great importance in the field of domestic water purification because, the conventional water treatment process is not capable of removing the toxic heavy metals and persistent organics generated from industrial and agricultural activities whereas, nanotechnology enabled water treatment process utilizing metal nanoparticles, nanostructured photocatalysts membrane and nanoadsorbents can elucidate and fix most of the water quality problems [9, 10].

Metal nanoparticles: Metals and oxides of metals such as silver, oxides of titanium and zinc are capable of disinfection because of antimicrobial activity due to their charge capacity [11]. Titanium dioxide (TiO_2) nanomaterial, works on the principle of semiconductor based photocatalysis and TiO_2 has low cost, good photo activity and non-toxicity in addition to production of highly reactive OH^- radicals which is responsible for disinfection of microorganisms such as, bacteria, fungi, algae, virus and all other pathogens in water [12]. Electro spinning is a method that offers the way to modify the surface properties of nanomaterials, it modifies different nanomaterials like TiO_2 by coupling it with secondary catalytic metal to enhanced water quality [11]. The development of visible light activated TiO_2 nanoparticles, make a significant impact on water purification process because, the controlled release of TiO_2 nanoparticles occurs when it is exposed to the visible light; this makes it responsible for water purification and reduction of organic carbon load through oxidative photochemical degradation [2,13].

Silver nanoparticles are also effective in disinfection of water without leaving the harmful disinfection by product (DBP), however, gold nanoparticle helps in oxidation of carbon monoxide contained in the water [14]. Although in antibacterial effect in water, silver nanoparticles (8 nm) were found to be most effective because of its smaller size, since larger particle size (11–23 nm) results in lower bactericidal activity [15]. Zero-valent iron nanoparticle structures (ZVI-NPs) were extensively used to dechlorinate the chlorinated organic compounds and immobilize the toxic heavy metals such as, hexavalent chromium, due to its powerful reducing property [16].

Magnetic nanoparticles*:* Magnetic nanoparticle with a size of 20nm has relatively high potential to remove toxic and carcinogenic chromium from water, with removal capacity of around 2μg Cr/mg in water. This is successfully applicable for small scale system because of its lower cost for the preparation of magnetic nanoparticles [17]. Iron incorporate into the water bodies through indiscriminate dumping of domestic and industrial waste, may leads to various health problems therefore, magnetically modified carbon nanotubes (CNTs) along with iron oxide nanoparticles on the surface, can have high potential to remove iron from drinking water and the nanocomposite prepared can be easily separated from the solution, after getting loaded with adsorbate [18]. Chang et al. [19] used super magnetic nano scale adsorbent of bayerite/SiO_2/Fe_3O_4 for de-fluoridation of water.

Nanoadsorbents: Various organic chemicals have been adsorbed more efficiently by carbon nanotubes (CNTs) than activated carbon. However, polymeric nanomaterial like dendrimers, are also able to remove both organic chemicals and heavy metals from water [4]. Among the recently developed nanoadsorbent for drinking water purification, the chemistry of noble metal nanoparticle is shown to be unique and the purification is possible when we practice the synthesis of noble metal nanoparticle and their reactivity at nanoscale [14].

Halogenated organics (pesicides), heavy metals, microorganisms can be removed by the application of noble metal nanoparticles. Meanwhile, silver nanoparticles have been used to remove the toxic contaminant found in drinking water, although the application of hybrid nanoadsorbent can successfully performed adsorptive removal of arsenic, fluoride and heavy metals than the utilisation of single nanoadsorbent [20]. Chai et al. [21] developed a novel adsorbent sulphate doped Fe_2O_3/Al_2O_3 for deflouridation of water. To generate pollutant-free drinking water, especially arsenic free water Attini et al. [22] synthesised a silica nanoparticle coated with goethite adsorbent for the removal of arsenic.

Nanomembrane: Generally, membrane treatment process is either pressure driven or electrical driven. Pressure driven treatment technologies include reverse osmosis, nanofiltration and ultrafiltration [23]. In recent years, new methodology have been developed which combines solar desalination and nanotechnology for the effective thermal desalination of water utilising low cost nanocomposite materials such as, plasmonic nanomaterials and graphite to enhance thermal desalination [24]. Conventional reverse osmosis membrane can be replaced by nanotechnology enabled materials such as zeolite coated ceramic membrane, thin film nanocomposite (TFM) membrane, protein-polymer biomimetic membrane, aligned CNTs membrane, self-assembled block co-polymer membrane and graphene based membrane for desalination of water and water reuse applications for domestic water treatment [25]. Development of thin film nanomaterial membrane mainly focuses on incorporating nanomaterials into the active layer of thin film composite (TFC) membrane via doping in the casting solution or surface modification [26,27]. Several studies in the literature reported widely use of biomemetic membrane which are chemically stable, highly permeable and selective in nature for the removal of salts from the water [28].

A type of pressure driven membrane process which is used in between reverse osmosis and ultrafiltration membrane is the nanofiltration membrane. Nanofiltration membrane process has peculiarity in higher rejection of the multivalent ions [29]. Nanomembranes multifunctional systems enable both particle retention and elimination of contaminants from the water and it is applicable for both decentralized treatment systems, point-of-use and heavily degradable contaminant, although, synthetic membranes are widely used in the desalination process [30].

Nanofibers and nanobiocides: Biofouling of membrane caused by bacteria has become a major problem of water treatment procedure and the nanobiocides incorporated electrospun nanofibers can solve this problem to some extent. Metal nanoparticles and engineered nanomaterials, are commonly used nanobiocides due to high antimicrobial activity. The life of the membranes can be improved by application of the nanobiocides incorporated nanofibers [31]. Electrospinning is the versatile technique used in the modification of the surface chemistry of fibers and it helps to create ultrafine fibers of various polymers with diameter up to few nanometer [32].

Nanoenzymes: Nanoenzymes are widely used in biofilms degradation because it has low toxicity and high biodegradability [1]. Biofilms are formed when sessile communities of bacteria encased certain extracellular polymeric substances (EPS). Biofilms often show reduced susceptibility to antimicrobials which has led to the invention of enzymatic degradation of biofilms, where enzymes are able to disrupt the structural stability of biofilm [33]. The Dominant component of biofilm includes protein and polysaccharide and hence the combination of protease and polysaccharases may be successful in biofilm removal. It is necessary to stabilize the enzymes through approaches such as enzyme modification, enzyme immobilization, protein engineering and medium engineering because, enzymes are highly unstable in nature and the immobilization can be improved by reducing the size of enzyme carrier, whereas nanoscale carrier material allows for high enzyme loading and enhances the enzyme activity [1].

Nano catalysts: High surface to volume ratio and shape dependent properties like zero valent metal, semiconductor materials and bimetallic nanoparticles are widely use in water treatment because, they can increase the catalytic activity at the surface thereby, enhancing the reactivity and degradability of contaminants such as organo chlorine pesticides, halogenated herbicides azo dyes, polychlorinated biphenyls, nitroaromatics etc. [34].

Bioactive nanoparticles: The difficulty in overcoming barriers to regional and national water supplies has lead to increased interest on point of use (POU) water treatment technologies at household and community level [35]. POU treatment technologies can avoid the obstacles associated with large scale treatments because, it is highly inexpensive method and entire unit can be purchase or constructed using easily available materials [10]. The utilisation of unconventional water sources such as storm water, contaminated freshwater, brackish water, etc. in developing countries due to limited freshwater supplies, makes the existing technologies coupled with huge centralized schemes not more sustainable in addressing problems related to water availability and stringent water quality standards [36].

Prakash et al. [11] synthesised silver nanoparticles with high antibacterial potential, which are extracellularly biosynthesised by *Bacillus cereus* bacteria exposed to different concentrations of silver salts, which makes bioactive nanoparticles to show great potential in the water purification [28]. Microbiological pollution is the most common biological contamination of drinking water distribution systems. Nanostructured materials, devices and processes were extensively used to eradicate these quality problems and the high performance nanostructured systems such as organic or inorganic composite and hybrid materials were also investigated for water purification [37].

Large scale purification: While selecting large scale techniques for water purification, two criteria are always taken into consideration. First consideration is, the technology should have disinfection capability to remove microbial contamination and the technology should be cost effective and applicable for domestic use in rural communities. Nanotechnology has already been used and found to satisfy both the criteria. Case studies on cost effective drinking water purification systems for developing countries particularly sub Saharan countries, uses PVC column packed with silver nanoparticle coated resins as filter systems, and their finding shows that, this emerging technology will provide a major contribution to solving the future problems associated with the scarcity of safe drinking water across the globe [38].

IBSA international cooperation: In South Africa, nanomaterials are utilised in water treatment extensively, therefore South Africa has created an international cooperation with other developing countries where nanotechnology has been extensively used for the water treatment. India-Brazil-South Africa (IBSA) concentrate on the three scopes of research, nanofiltration and ultrafiltration membranes, nano-based water purification system for remote and rural areas through carbon nano gels, nanotubes and nanofibers [39].

Large scale desalination: There are more than 7,500 desalting plants in operation worldwide producing several billion gallons of water per day, among which 57% are in the Middle East and 12% of the world capacity is produced in America, with most of the plants located in the Caribbean and Florida [40]. Large-scale desalination typically requires large amounts of energy and specialized infrastructure and the large energy reserves of Middle Eastern countries, along with their relative water scarcity, have led to extensive construction of water desalination plants in those regions. The desalination is increasingly growing in the Middle East and North Africa (MENA) due to the increase in water demand and reduction in desalination costs resulting from advances in desalination technologies [41].

Membrane based nanotechnology for water desalination mainly includes, reverse osmosis followed by ultra-filtration and nano-filtration. Different concentration of silver nanomaterial and graphene can be used to enhance the photothermal conversion which can in turn, enhance the rate of water vaporization. Water quality test such as turbidity, acidity, alkalinity, heavy metals, ions, salts and microorganism of the water treated using this technology confirms that, the water samples are ultrapure [24].

Novel innovations: Novel technologies have been developed in recent years which are applicable at both domestic as well as large scale treatments to overcome the drawbacks of nanotechnology. For example, iron hydroxide, one of the primary components of rust normally poses health hazards to human. Studies reveals that, this compound can be converted into an environment friendly coating that can continuously absorb the pollutants from water, however, it is decided to attach iron hydroxide nanomaterials on a sponge-like support known as, nickel foam which helps to trap and remove contaminants from dirty water. Studies conducted on water contaminated by a dye pollutant “Congo red”, reveals that 90% of dye has been removed within half an hour and water become almost colourless. Electron microscopic studies revealed that, the small elongated fin like projections on coating, helps to increase surface area and thereby removal efficiency [42].

Alzate et al. [43] studied functionalized cotton (CD-TFP@Cotton) which can be produced by covalently functionalized cotton fabric with a porous β-cyclodextrin, the resulting functionalized cotton can adsorb organic micropollutants such as bisphenol-A from water with speed and efficiency ten times greater than the untreated cotton. Functionalized fabric can also separates volatile organic compounds (VOCs) at saturated and environmentally relevant vapour pressure, which makes cotton suitable for water purification membranes, odor controlling fabrics, and respirators that control exposure to VOCs.

Adsorption and removal of dyes such as methyl blue (MB) and methyl orange (MO) from the water, can occurs with mono-dispersed hybrid nanoparticle (Ag2S@Ag) developed from laser ablation of silver (Ag) metal in activated liquid containing thioaetamide (TAA), hexadecyl trimethyl ammonium bromide (CTAB) and distilled water. This hybrid nanoparticle is responsible for adsorption, agglomeration and deposition of adsorbent due to the charge difference between active site of adsorbent and SO_3 functional group [44].

Reduced graphene oxide (rGO) sheets within paper based nanocomposite can remove organic contaminants through physical adsorption when it exposed to solar radiation, the porous-structured paper-based nanocomposites allows incorporation of photocatalysts with combined adsorption, photodegradation and interfacial heat-assisted distillation mechanisms, which is aimed at multifunctional solar driven clean water generation [45].

Virus is the most dangerous water-borne infectious microorganisms and they are not prone to disinfection and are difficult to be remove by filtration studies made by scientist at Uppsala University construct a simple paper made by cellulose nanofibers (mille-feuille) which is highly efficient in removing virus from water. Cellulose is one of the most commonly used filtering media and the previous studies suggest that, large viruses such as influenza virus can be removed by using filter paper with large pores, whereas Mille-feuille filter can remove virus with low fouling, high flow and long life-time along with production of therapeutic proteins and vaccines [46].

*E.coli*is one among the deadly contaminant in drinking water. Sushanta [47] developed a hydrogel based rapid *E.coli* detection system for the treatment of contaminated drinking water. This device is mainly made by nano hydrogel matrix that encloses specific enzymatic substrate, where these substrates induce the release of some enzymes in *E.coli* cells, which can produce a response, thus a red colour is appeared and if there is no *E.coli,* due the lack of chemical reaction, the colour of the hydrogel remain unchanged.

Incorporating a photoisomeration of a photoswitchable surfactant molecule with a cationic head-group into aqueous carbon nanomaterial systems, it is possible to control the dispersion state of these materials using only light as a clean and low energy external stimulus. surfactant molecule adsorbed to the surface of the carbon-based nanomaterials, such as graphene oxide (GO), reduced graphene oxide (rGO) and CNTs undergoes separation and re-dispersion in the presence of UV radiation within the range of 365 nm. Thus the surfactant molecules changes from trans to cis isomer, which will increases their aqueous solubility [48,49]. It will alter the adsorption affinity of the surfactant molecules on to the GO and rGO, it results in easy recovery of surfactant molecule from water [50].

Nanotechnology plays a vital role in drinking water purification, but there are still potential drawbacks and the major challenges including cost of nanomaterial and scaling up of nanobased treatment process for commercial use. Health and safety issues may arises when nanobased materials are extensively used in the domestic water industry, especially where the nanomaterials get reached into the natural resources [3].

CONCLUSION

The advances in nanotechnology and their small scale and large scale applications for domestic and industrial water purification have been discussed in the present contribution. The methods include membrane techniques for desalination, disinfection and decontamination, biosorption and nanoadsorption for contaminant removal, nanophotocatalysis for chemical degradation of contaminants, nano sensors for contaminant detection and different membrane technologies including reverse osmosis, nanofiltration and ultrafiltration for contaminants separation from the water. The environmental fate and toxicity of a nanomaterial is one among the drawbacks of nanotechnology, to overcome the drawbacks, the novel technologies have been developed in recent years which includes functinalized cotton, iron hydroxide coatings, nano-hydrogel and mono-dispersed hybrid nanoparticle and it is applicable for both domestic as well as large scale treatments. This review opens up new areas in research in developing new nanomaterial coating substances for carbon nanotubes, various nanoparticles and hydrogels.

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