Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2013.801789

52 (2014) 4089–4101
June

Taylor & Francis
Taylor & Francis Group

Emerging nanotechnology-based methods for water purification: a review

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Received 10 January 2013; Accepted 26 April 2013

ABSTRACT

Nanotechnology has a wide range of applications. This makes it a very important technology of the future. Its application in water and wastewater purification is of great interest not only in developing countries but also in the developed countries. The application of nanometals (silver and gold) and nanomembranes can help in developing of water treatment technologies which can be used for solving water-related problems such as waterborne pathogens, biofouling, removal of toxic metals (lead, arsenic, and chromium), etc. Moreover, nanotechnology can also be used to increase the efficiency of water filters. In this paper, we review the emerging nanotechnology-based methods for water purification, the potential applications of nanotechnology in the form of nanosensors, nanomembranes, nanometallic particles, and photocatalysis for water purification, nanosensors for detection of contaminants in water, novel magnetic nanoparticles for water desalination, and finally we present the possible risks associated with the use of this technology.

Keywords: Water purification; Nanotechnology; Conventional methods; Nanoparticles; Nanomembranes; Nanosensors; Nanofiltration

1. Introduction

Water is an important resource because the existence of life depends on it. Water is essential for a variety of activities such as in agriculture, industries, households, recreation, and environment. It is important to remember that only 2.5% of earth' s water is fresh and around 90% of this is locked up in polar ice caps and deep groundwater reservoirs [1].

Water supply is already well short of demand in many parts of the world, especially among the developing countries. It is anticipated that many more countries will experience this disequilibrium in the near future. Due to the ever increasing human population, water consumption is growing, resulting in the depletion of many of the world's major aquifers. It is therefore imperative that whatever water resources are available they should be managed properly. Water contamination especially in the developing

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countries is another serious problem as it poses serious health risks.

Water purification is an essential process of removing undesirable contaminants such as bacteria, viruses, toxic metals, etc. Water purification is of great significance in developing countries such as Pakistan where a number of diseases disseminate through water supply [2]. Diarrhoea is the most common outcome of contaminated water. In 2010, 4.4 million children under five years of age died from infectious diseases worldwide and diarrhea was one of the leading cause of their death [3]. Scientists and engineers have an important role to play in reducing this disequilibrium by developing techniques that can be used efficiently and cheaply to provide safe drinking water to the affected people. Different review articles have shown the importance of nanotechnology, use of nanomembranes for water purification, nanoscale iron particles for environmental remediation [4–6]. In this article, we discuss some recently developed nanotechnology methods that have been employed to remove biological and chemical contaminants and present overall picture of methods used for water purification. In spite of the fact that conventional methods have been available to us for many years, their use is limited in less developed countries because of their cost. We argue that nanotechnology may provide us with a cheap and affordable alternative to these conventional methods. We present the current status of research and development activity in the field of nanotechnology regarding purification of water and comparison with the conventional methods. Finally, we discuss the risks that are required to be addressed before nanotechnology can be employed to its full potential in providing safe and affordable drinking water to the less privileged population.

Table 1
Properties of materials at nanoscale [10]

Electrical	Higher electrical conductivity in ceramics and magnetic nanocomposites; higher resistivity in metals
Magnetic	Increase in magnetic coercivity down to a critical size in the nano regime; below the critical crystalline size, decrease in coercivity leads to superparamagnetic behavior
Mechanical	Increase in hardness and strength of metals and alloys; enhanced ductility, toughness and form ability of ceramics; super strength and super plasticity
Optical	Increase in luminescent efficiency of semiconductors; transparency of nanoparticles
Chemical	Substantial increase in catalytic properties and reaction rates

2. Nanotechnology and its potential applications

The word Nano is derived from a Greek word which means "dwarf". A nanometer can be defined as one billionth (10^{-9}) of a meter, which is equal to about 10 hydrogen atoms in length. An average human hair is about eighty thousand nanometers wide. The concept of nanotechnology was given by Noble Laureate Professor Richard Feynman in his famous lecture in 1959, "There is plenty of room at the bottom" [7].

Scientists were unknowingly using matter at nanoscale for hundreds of years. It was not until the invention of a new generation of electron microscopes, such as scanning tunneling microscope and atomic force microscope, in 1980s that allowed the scientists to produce new materials with new properties due to opportunity of synthesis of nanoparticles with required characteristics such as sizes and distribution of sizes, form of nanoparticles, etc. Efficient systems with better performance can be obtained by incorporation of nanoscale materials into industrial products. Nanotechnology has been developing at a very fast rate. It has been called another "Industrial Revolution" and as of 2009, this new knowledge supported about a quarter of a trillion dollars market worldwide. By 2020, the increasing integration of nanoscale science and engineering knowledge and of nanosystems, promises mass applications of nanotechnology in industry, medicine, and computing and in better comprehension and conservation of nature [8]. This interdisciplinary field draws expertise from different disciplines of science. Up till 2009, nanotechnology had captured the market with over 2,500 different products, opening vast avenues for world economy to grow in coming decades [9].

At nanoscale, the physical, chemical, biological, mechanical, electrical, and magnetic properties, etc. of the materials change drastically, as shown in Table 1 [10].

2.1. *Applications of nanotechnology in water purification*

Nanotechnology has played a key role in addressing the problems related to water purification and water quality. Nanomaterials have potential applications in disinfection and microbial control of water. Various natural and engineered nanomaterials have manifested potent antimicrobial properties via diverse mechanisms including photocatalytic production of reactive oxygen species that damage cell components and viruses (e.g. TiO_2, ZnO, and fullerol) compromising the bacterial cell envelope (e.g. peptides, chitosan, carboxyfullerene, carbon nanotubes (CNTs), ZnO, and silver nanoparticles (nAg)), interruption of energy transduction (e.g. *n*Ag and aqueous fullerene nanoparticles (*n*C60)), and inhibition of enzyme activity and DNA synthesis (e.g. chitosan) [11]. Nanomembranes have also been employed very successfully to produce potable water. More over nanosensors have been developed that can very effectively detect single cells.

2.1.1. Antibacterial activity of silver nanoparticles

Antibacterial activity of silver (Ag) is very well known from history. Silver is appearing more frequently in textiles, cosmetics, and even domestic appliances. It is worth mentioning some examples, such as inorganic composites with a slow silver release rate, which are currently used as preservatives in a variety of cosmetic products [12]. Another current application includes new compounds of silica gel microspheres containing a silver thiosulfate complex, which are mixed into plastics for long-lasting antibacterial protection [13]. These compounds act against a variety of drug-resistant bacteria, which makes them a potential candidate for use in pharmaceutical products and medical devices [14,15]. Silver in various forms, inactivates viruses by denaturing enzymes [16–18]. Several investigators have assessed the biocidal efficacy of silver nanoparticles [19–21]. Silver significantly reduces waterborne pathogens such as *Pseudomonas aeruginosa* and *Aeromonas hydrophila* by inactivating them. It can also be used as a secondary disinfectant [22]. Scanning and transmission electron microscopy were used to study the biocidal action of silver nanoparticles against *Escherichia coli*. The results confirmed that the treated *E. coli* cells were damaged, showing formation of "pits" in the cell wall of the bacteria. Nontoxic nanomaterials prepared in a simple and cost-effective manner may be suitable for the formulation of new types of bactericidal materials [23]. In another study, the bactericidal effect of silver nanoparticles obtained by a novel electrochemical method on *E. coli, Staphylococcus aureus, Aspergillus niger, and Penicillium phoeniceum* cultures were studied. The silver nanoparticles showed a pronounced antibacterial/antifungal effect [24]. The antimicrobial activity of silver nanoparticles and $AgNO_3$ were compared against *E. coli* in terms of growth rate, time dependency, and zone of inhibition. Ag nanoparticles created a zone of inhibition of 1.7 cm as compared to 0.8 cm by $AgNO_3$, thus proving Ag nanoparticles to be the efficient candidate for antimicrobial activity [25]. Similarly, another study on bactericidal effect of silver nanoparticles against gram negative bacteria showed that the effect is size dependent. The most effective range of nanoparticle size that provides direct interaction with the bacteria have a diameter of about 1–10 nm amongst the tested range of 1–100 nm [13].

A number of studies have reported the effective use of nanomaterials in water specific field (Table 2). Silver nanoparticles, CNTs, and fullerenes can be used for their biocidal actions against bacteria, viruses and fungi, and in water filtration, water quality assessment, and removal of small contaminants. There is need to develop such products that do not leach nanoparticles in the final drinking water [39]. Silver-impregnated polymers do not pose any significant health risk at $< 0.1\,mg/\sim$ and could be tolerated without any health risk [40].

2.1.2. Use of silver for water purification

Use of silver nanoparticles for water purification is already being practiced in both the advanced and

Table 2
Applications of nonmaterials in water-related specific fields

Applications of nanomaterials	Specific field	References
Silver nanoparticles, fullerenes and CNT as antimicrobial	Broad spectrum antibacterial and antifungal, viricidal agent	[14,16–18,20,21,26–33,79]
	Dental work and catheters	[34–36]
	HIV, hepatitis B virus (HBV)	[37,38]
Silver nanoparticles and CNT as water purifier	Water filters/removal of contaminants	[41,43,44,75,88]
	Nano-membranes	[80,86,88,90,93]
	Desalination	[91,100]
Nanosensors	For detection of biochemical small particles	[66–67]
	Detection of viruses	[69]
	For water quality	[70–72]

developing countries. Clay filters strengthened with husk and coated with colloidal silver were produced for the survivors of Tsunami in Sri Lanka to provide safe drinking water for the devastated area [41]. These filters were produced on large scale for emergency relief operations.

Use of Ag-nanoparticles with ultrasonic radiation for short time period against the coliform bacteria enhances antibacterial effect [42]. Water filters made up of silver nanoparticles coated on polyurethane foam were used and no leaching of silver nanoparticles was observed. Excellent bacteriological analysis results were reported in which no growth of *E. coli* was observed in the outflow of water. This low-cost technology for purification of drinking water meets the bacteriological WHO recommended standard for drinking water [43]. Polypropylene filters coated with nano silver particles (45 nm) were reported for use in water purification. After the filtration period of 6.5 h no bacteria was detected in the water sample when the input water had the bacterial load of 10^3 CFU/ml. Nano silver-coated filters were found to be completely effective against *E. coli* and the leaching of silver nanoparticles in the filtered water sample was nil when examined by inductively coupled plasma/mass spectrometry, suggesting the possible use of nano silver-coated filters in water purification [44]. These studies indicate the effective use of nanomaterials for the detection of coliform bacteria and removal of waterborne pathogens. These studies also show no leaching of silver during the experiments indicating no health-related risks involved in the use of nanomaterials.

2.1.3. Use of nanoparticles by photocatalysis

Photocatalysis is the phenomenon of overcoming the activation energy or temperature of a chemical reaction by light. Advanced oxidation processes paired with sunlight present an attractive option for water treatment by generation of OH radical [45]. Photocatalysis can be used to break down a wide variety of organic materials, organic acids, estrogens, pesticides, dyes, crude oil, microbes (including viruses and chlorine resistant organisms), inorganic molecules such as nitrous oxides and, in combination with precipitation or filtration, can also remove metals such as mercury [46]. The limitation of using nanoparticles for water purification is the removal of these particles from water after treatment which has necessitated the use of photocatalyst supports, which can be regenerated and can be conveniently removed. Efficacy of photocatalysis in the detoxification of a wide range of industrial and agricultural effluents is well documented [47].

Semiconductor photocatalysis has received much attention as a potential solution to the worldwide energy shortage and for counteracting environmental degradation [48]. Photocatalysis, using nanostructures of metal oxide semiconductors such as zinc oxide (ZnO), titania (TiO), tungsten oxide (WO_3), zinc stannate (Zn_2SnO), etc. is an attractive way of water purification as it is capable of removing chemical as well as biological contaminants [49–53]. Photocatalysis of titanium dioxide for wastewater treatment is a preferred choice due to its abundance and low cost [54]. During photocatalysis, the photocatalyst is illuminated and activated. The activated photocatalyst promotes the formation of reactive hydroxyl radicals, which in turn breakdown organic pollutants resistant to biological degradation in water. Nano titanium dioxide photocatalytic oxidation used in water treatment has the more obvious advantage of very high reaction rates due to high-specific surface areas and low mass-transfer restrictions [55] unmatched by other conventional methods, especially when there are high concentrations of organic pollutants in water [56].

Heterogeneous photocatalytic systems of TiO_2 and ZnO, are capable of operating effectively and efficiently for waste water treatment [57]. A photocatalyst made up of titanium oxide fibres on gird that is instilled with nitrogen, to kill bacteria has been developed at University of Illinois. When visible light hits the fibers on a gird a positive charge is produced which breaks open the water molecules, yielding a substance lethal to microbes. If Palladium nanoparticles are added along with the photocatalyst, this will increase the efficiency of the photocatalyst, as these hold the positive charge for longer times. The photocatalyst reduces the concentration of bacterium *E. coli* in water when kept under a lamp for one hour, producing safe drinking water [58].

The process of photocatalysis had been innovated for water detoxification and cleaning [59]. Nanocomposite of titanium dioxide and silver nanoparticles was found stable and could be used repeatedly under Ultraviolet (UV) irradiation for degradation of Rhodamine B and disinfection of *E. coli* in water [60]. Photocatalyst beads that can be separated magnetically were prepared, containing nano-sized iron oxide in alginate polymer, to reduce chromium (VI) in water. Results showed significant photo-reduction of chromium (VI) at low pH [61]. A nanocomposite photocatalysis was developed by using maghemite (–Fe_2O_3) as a photocatalyst for the reduction of the aqueous pollutant chromium (VI) to chromium (III), which is relatively less toxic and inert than chromium (VI).

Conventional methods to eliminate chromium (VI) from near dilute solutions are not suitable. The alumino-silicate nanocomposite with metal oxide photocatalyst was effective in sequestration of metal ion and destruction of organic contaminant [62].

Conventional method of photocatalysis used for water purification can be made effective by using titanium dioxide (TiO_2) and zinc oxide nanostructures. Using this process, *E. coli* concentration in water was decreased to a safe level in just one hour [63]. TiO_2 and ZnO photocatalysis has emerged as a promising alternative technology for the disinfection of industrial effluents and drinking water, and have several advantages [64,65,51].

2.2. Nanosensors for water quality analysis

New sensor technologies have been developed by combining fabrication strategies at microscale and nanoscale to create small, portable, and highly precise sensors that can detect the most minute amount of chemical or biochemical substance in water [66]. Nanosensors consisting of different nanomaterials such as CNTs both single-walled and double-walled, nanowires (V_2O_5, SnO_2, ZnO, etc.), quantum dots, nanocantilevers, and metal nanoparticles (Ag, Au, Cu, etc.) are being used for this purpose. Magnetic nanosensors are used to detect smaller particles with sensitivity in femtomole range (0.5–30 fmol) such as mRNA, proteins, enzymatic activity, and pathogens [67]. Boron-doped silicon nanowires were used to create highly sensitive, real-time electrically based sensors for the detection of biological and chemical species [68]. In another study, electrical detection of single viruses was reported by using nanowires (Fig. 1). It was noted that the electrical conductance changes in the presence of viruses such as influenza A, excluding Paramyxovirus or Adenovirus. Multiple viruses can be detected in parallel [69].

Water quality analysis can also be carried out by using nanosensors as these are used for the detection of *E. coli* and other indicator bacteria. One can detect bacteria in much less time, as nanosensors flash light on the presence of bacteria in the samples. One can save time and money by using nanosensors for the detection of microbes in water samples. Different nanomaterials such as quantum dots, nanoshells, and CNTs are used in the nanosensors for water quality analysis [70]. Another method was used for the inactivation of bacteria by using cotton, silver nanowires, and CNTs. It was reported that this gravity fed device (Fig. 2) operating at 100,000 $l/(hm^2)$ can inactivate >98% of bacteria at several seconds of incubation time [71].

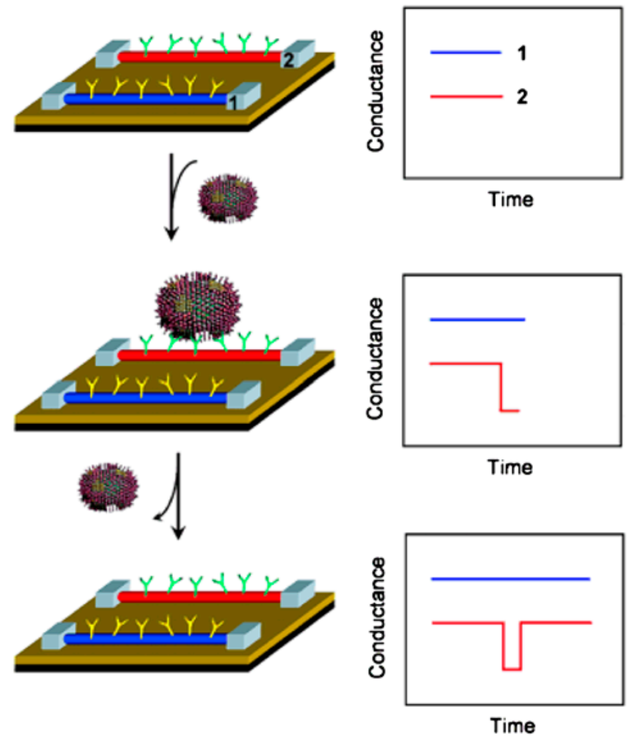

Fig. 1. Nanowire-based detection of single viruses. (Left) Schematic shows two nanowire devices, 1 and 2, where the nanowires are modified with different antibody receptors. Specific binding of a single virus to the receptors on nanowire 2 produces a conductance change (Right) characteristic of the surface charge of the virus only in nanowire 2. When the virus unbinds from the surface the conductance returns to the baseline value [69].

Among the methods available for the detection of waterborne pathogens are biochemical identification and molecular methods but this requires large number of protocols and is also a time-consuming process. Different nanotechnology-based methods for the detection of bacteria by using gold nanoshells conjugated with antibodies are mentioned in Fig. 3 [72]. Antibodies recognize the antigens and by using IR radiation at 808 nm for 5 min at 1 $W cm^2$ the transfer of energy causes the bacterial cell lysis. In this study, *E. coli* and *Bacillus subtilis* were used for biorecognition and efficiency of gold nanoshells was tested.

Another nanosensor technology in which normal papers dipped in solution containing CNTs and antibodies was used to detect toxins (microsystine LR) present in water by affecting the conductivity of CNTs. This change in conductivity can be detected by a measuring device [73].

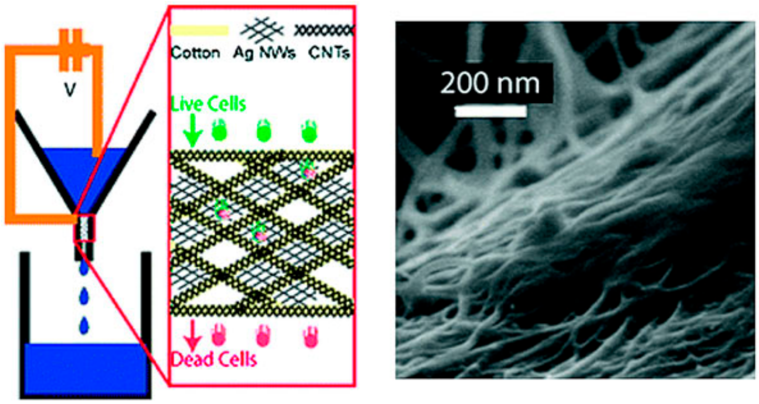

Fig. 2. Schematic, fabrication, and structure of cotton, AgNW/CNT device (A device made by using cotton, silver nanowires and CNTs) [71].

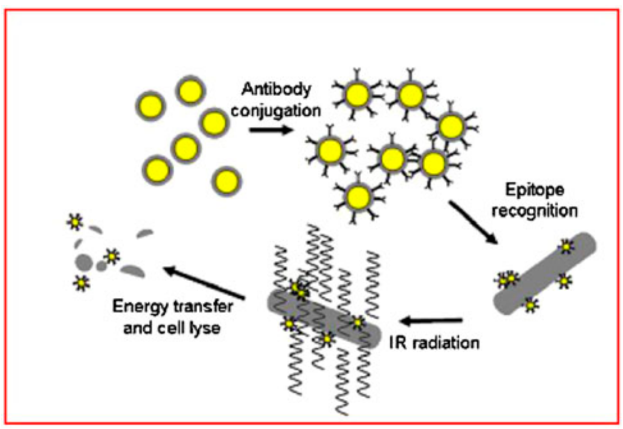

Fig. 3. Schematic representation of conjugation of nanoshells with antibodies, antibody-antigen recognition, exposure to IR radiation and transfer of energy causing lysing of target species [72].

2.3. Novel nanomaterials for water purification/desalination

Water treatment processes and technologies have been going through advancements over time. Development of novel nanomaterials opens new arena for improved water purification at surface and ground, wastewater from industries polluted with metals, organic and inorganic solutes, radio nuclides, and micro-organisms [74].

Researchers applied green nanotechnology by using gold nanoparticles and polydimethylsiloxane (Au NP/PDMS) nanocomposites for applications in biomedical, optical, water purification, and microfluidic systems. For water purification applications, the method was used for removing aromatic solvents and sulfur-containing contaminants [75]. Nanoparticles of aluminum salts are also reported for water treatment and disinfection [76]. A potassium manganese nanowire "paper towel" has selectivity for oil absorption with great efficiency, which can be recovered, by heating the mat, and reused [77].

Halogenated organic compounds can be selectively removed from wastewater by usingnanoscale palladium on magnetite catalyst (Pd/Fe_3O_4), which is very active and magnetically extractable. This technique is sensitive to the presence of heavy metals and sulphides which is a drawback. These components require removal before catalyzation by palladium fordehalogenation [78]. Nanoscale materials for water purification can be divided into four classes: (1) dendrimers (2) metal nanoparticles (3) zeolites, and (4) carbonaceous nanomaterials. CNTs and nanofibers showed some positive results. Good results were obtained with nanomaterials as compared to other techniques used in treatment of water due to their high surface-to-volume ratio [79].

CNT membranes and nanomesh are two very feasible choices for water purification. A nanomesh that filters out cysts, parasites, fungi, micro-organisms, viruses, and many mineral toxins from water has been developed. It is composed of CNTs placed on a porous substrate flexible enough to be used as a flat paper-like filter or rolled into conventional cylindrical structure. It can rapidly purify water from river, ground well, or even mud puddle [70]. Application of two types of CNT-based membranes (i) Bucky-papers and (ii) isoporous CNT membranes have been studied. Both of these membranes have distinctively different structures and porosity [80]. Nanoparticles have also been analysed for improved performance of membranes used for water purification [81]. Scott et al. [75] described the use of Au NP and PDMS composite in aqueous medium which was used for water purification. By this method, contaminants can be removed and material can be reused. Chinese scientists have developed a new low-priced magnetic sorbent material to remove heavy metal from water. Iron oxide magnetic nanoparticles (Fe_3O_4-magnetite) were coated with humic acid that greatly enhanced stability of the material and increased removal efficiency of heavy metals with negligible leaching of nanoparticles [82]. Nanomagnetics, a British Company, has prepared magnetic nanoparticles which are active against viruses, bacteria, fungi, etc. and can also desalinate water. These magnetic nanoparticles were also used by US Army in Afghanistan and Iraq [83].

Scientists in USA recently prepared highly efficient recyclable antibacterial magnetic nanoparticles, consisting of a magnetite (Fe_3O_4) core with an antibacterial poly quaternary ammonium (PQA) coating. The PQA-modified magnetite nanoparticles were 100% biocidal against *E. coli* and easy to remove from water [84]. Foam (porous) of PDMS incorporated with Au NP (10–50 nm) had been used for the removal of organic compounds from water. PDMS is low in density and has the ability to compress highly. It swells by 600% against compounds such as benzene, toluene, ethyl benzene, and xylene which are volatile in nature. Therefore, it is effectively used for removal of oil spills from water. It is claimed that this material is immune to rough chemical environments and effective against contaminants such as thioanisole which contain odorous sulfur. It can also show promising applications as food packaging material [85].

2.3.1. Nanomembranes for water purification

Separation membranes with pore sizes at nanoscale reduce the cost of methods employed for production of potable water. Several polymeric nanofiltration membranes (NF) were studied for the treatment of brackish groundwater in South Africa. The results showed that potable water can be produced from brackish groundwater by using NF [86]. It is reported that CNTs, dendrimers, and other nanoparticles are cost effective and more efficient for advanced water purification and desalination. There are two types of effective nanotechnology membranes: (i) nanostructure filters (CNTs, nanocapillary array) and (ii) nanoreactive membranes (nanoparticles) [87].

Filters made up of CNTs were used for the removal of bacterial pathogens from contaminated water. These cylindrical filter membranes were shown to remove *E. coli, S. aureus*, and *Poliovirus* sabin 1, and were re-usable by cleaning with ultrasonication or autoclaving [88]. Defective CNTs were used to develop nanostructured material for purification of fluids including applications for water purification, liquids, and gases [89].

It is reported that permeable reactive barriers (FeO/FeS nanocomposites) could be constructed by using dendrimers as templates for the remediation of ground water [90]. CNTs could be incorporated in membranes for a promising water desalination process. These membranes accomplish a high degree of desalination using reverse osmosis at flow rates far in excess of the existing membranes [91].

Nanofabrication methods are used to develop novel nanocapillary array membranes. These membranes have the property of increased solute retention with minimal fouling tendency [92].

2.3.2. Nanotechnology-based water filtration

Clay filters have been in use for many years to produce potable water. American Red Cross produced and distributed some 10,000 clay filters in Sri Lanka for approximately 50,000 people in 2007 [41]. Ceramic water filter has shown promising results in Cambodia. Accessibility was made possible especially to the poorest, with a cost of US$ 7.50–9.50 per system. The ceramic water purifier resembles a flower pot having porosity equal to or less than 1 μm. Water flows at the rate of 1–3 l/h and the maximum capacity is 10 l of water per day [93]. An Indian company has launched a water filter "Tata Swach" which is entirely based on affordable natural ingredients for delivering water fit for drinking. Maximum capacity of the water filter is 3,000 litre after which the filters shut down as the cartridge stops working. It is portable and economical, as it costs Rs. 30 (US$ 0.3) a month for a family of five. This product and technology has generated fourteen patents [94]. Seldon Laboratories US, has developed a cost-effective mass production system for "nanomesh" manufacturing. Nanomesh is composed of CNT that can be placed on a flat substrate to form a paper-like filter or can be wrapped around any conventional cylindrical filter. Based on nanomesh technology, Seldon has produced a pencil-sized, straw-like portable water filtration device prototype known as the "water stick", which can remove more than 99.99% of bacteria, viruses, cysts, spores, moulds, coliform, parasites, and fungi and also significantly reduces lead and arsenic. Functionalized versions of nanomesh can remove organic as well as inorganic contaminants and can be coated with an antibacterial agent to prevent bio-film formation [95].

Sky Hydrants developed by Siemens AG can treat brown sludge into clean drinking water. This ultrafiltration device is self-cleaning which consists of three large cartridges each containing 10,000 minipipes made from thin membranes which have openings 100 nm in diameter that keep dirt and bacteria from passing through [96]. Nanofiltration is a better process and has low operational cost [83]. A Korean company Saehan Industries has developed a device that incorporates NF with pre- and post-treatment filters for household water purification without the use of a storage tank. Storage water tanks can increase the risk of water recontamination if water is stored too long or with improper sanitation. Saehan's NF device can be used to remove almost all water contaminants, including bacteria and heavy metals. It is also effective for desalination because it removes 90% ion contaminants and salts. Saehan's technology has been field tested in China and Iran for drinking water treatment and desalination [95].

A US-based corporation offers nanofibrous adsorbent technology with its line of NanoCeram® filter media and cartridge filters, which are made with electropositive alumina nanofibers. The alumina nanofibers have more available surface area than conventional filter fibers and exhibit a higher electropositive charge, which allows them to adsorb significantly more negatively charged contaminants such as viruses, bacteria, and organic and inorganic colloids at a faster rate. NanoCeram® filters remove and retain over 99.99% of viruses, bacteria, parasites, natural organic matter, DNA, and turbidity. The filters have also been shown to adsorb 99.9% of salt, radioactive metals, and heavy metals such as chromium, arsenic, and lead. NanoCeram® filters are cheap to produce because they can be manufactured using papermaking technology. The filter media currently cost US$ 10 per square meter, but may cost US$ 3 per square meter once mass produced. Cartridge filters cost US$ 75 per 20–200 filters, depending on diameter [97]. US-based KX Industries has developed World Filters, a line of gravity-flow filtration devices containing nanofibers specifically for use in developing countries. World Filters reportedly remove over 99% of bacteria, viruses, parasites, organic contaminants, and other chemical contaminants. The household scale World filter device can produce 378 l of water per filter at a rate of 4–6 l/h. The household device is expected to retail for US$ 6.00–11.00, with replacement filters costing US$ 0.80–0.90 each, translating to US$ 0.002 per litre of water [95]. Another US company SolmeteX, Inc. produces ArsenX™, an adsorbent resin made of hydrous iron oxide nanoparticles on a polymer substrate that is used for removing arsenic, uranium, chromium, antimony, and molybdenum in 2.5–3 min of contact time. It is reported to generally range from US$ 0.07–0.20 per thousand litres, including amortized capital costs and operation and maintenance costs [98].

3. Nanotechnology-based methods vs. conventional methods for water purification

Problems related to water are expected to grow worse in the coming decades, with water scarceness happening globally, even in regions presently considered water-rich. Robust new methods of purifying water at lower cost and with less energy, while at the same time minimizing the use of chemicals and impact on the environment are required [99]. Nanotechnology shows great promise as a feasible means of treating both long-standing and emerging water contaminants, as well as enabling technologies such as desalination of seawater to increase water supply [100]. Amongst the top 10 applications of nanotechnology for developing world "Water Treatment and Remediation" stands at number three (Fig. 4) [101].

Conventional methods for water purification have been used since old times in the developing as well as developed countries. Conventional water treatment technologies include filtration, ultraviolet radiation, chemical treatment, and desalination, whereas the nano-enabled technologies include a variety of different types of membranes and filters based on CNTs, nanoporous ceramics, magnetic nanoparticles, and other nanomaterials [86]. Conventional methods have certain drawbacks. The disadvantage of chlorination of drinking water is the possible synthesis of toxic chlorinated fragments. Ozone and chlorine dioxide seem to produce fewer carcinogenic by-products but the risk for acute toxicity, especially from the chlorites which follow chlorine dioxide, is higher than with

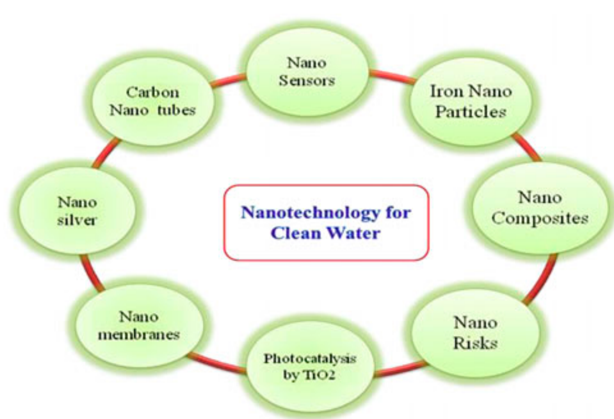

Fig. 4. Summary of nano-technologies used for water purification.

chlorine. In different cases, UV can also be used as an alternative to chlorination but the drawback is UV alone cannot decrease the concentrations of organic contaminants of the treated water [102,103]. Protozoan cysts such as *Cryptosporidium parvum* oocysts are resistant to removal and inactivation by conventional water treatment (coagulation, sedimentation, filtration, and chlorine disinfection) [104]. For drinking water production, microfiltration and ultrafiltration is used to satisfy the turbidity, particle and micro-organism removal requirements. But these processes require pretreatment of water otherwise a large percentage of disinfection by-products precursors will be left unresolved [105]. Fouling is another main problem in conventional membrane-based water treatment [106]. Slow sand filtration is the least complicated from operator's perspective and effectively removes cysts, viruses, and bacteria but it is less effective for removal of trihalomethane precursor or organic chemicals. It gives the operator the least ability to change treatment in response to changes in raw water [107].

The potential of nanotechnology is well estimated to overcome the technical problems of removing contaminants, to provide potable water to people of both developed and developing countries. Nanotechnology is already being used for removal of sediments, chemical effluents, charged particles, bacteria, and other pathogens. Toxic trace elements such as arsenic and viscous liquid impurities such as oil can also be removed. The main advantages of using nano filters, as opposed to conventional systems, are that less pressure is required to pass water across the filter, and they can be more easily cleaned by back-flushing compared with conventional methods [108]. Filtration membranes with TiO_2 nano-thorn eliminates the problem of membrane fouling present in conventional systems and provides high-quality water with increased water flux [109]. Nanoporous zeolites, attapulgite clays (which can bind large numbers of bacteria and toxins), and nanoporous polymers (which can bind 100,000 times more organic contaminants than can activated carbon) can all be used for water purification [110]. Tiny particles of pure silica coated with an active material could be used to remove toxic chemicals, bacteria, viruses, and other hazardous materials from water much more effectively and at lower cost than conventional water purification methods [111]. Point of use based CNT technology can possibly avoid difficulties of treating biological contaminants in conventional water treatment plants, and thereby remove the burden of maintaining the biostability of treated water in the distribution systems [112]. These membranes have also been identified as promising for desalination and as an alternative to reverse osmosis membranes. The cost of producing CNT membranes continues to decrease as researchers develop new and more cost-effective methods to mass produce them. CNT membranes are expected to be more durable and easier to clean and reuse than conventional membranes without a decrease in filtering efficiency. CNT desalination membranes are expected to reach the market in 5–10 years. Researchers are currently working to overcome challenges associated with scaling up the technology [95]. Another nanocarbon-conjugated polymer nanocomposite method using nanocarbon colloids and polyethylenimine for water purification from metal ions reported greater than 99% sorption of Zn(2+), Cd(2+), Cu(2+), Hg(2+), Ni(2+), Cr (6+) ions [113].

Several technologies have been studied as a possible low-energy replacement for conventional reverse osmosis membranes in desalination and water reuse applications. Nanocomposite membranes exhibit one to three times the water permeability with the same rejection as commercial RO membranes and can be imparted with antimicrobial and photo-reactive functionality [114]. Nanotechnology provides inexpensive, portable, easily cleaned systems that purify, detoxify, and desalinate water more efficiently than do conventional bacterial and viral filters. Nanotechnology-based methods for producing clean water have an important role to play due to their higher efficiency, cost-effectiveness, and incredibly large surface areas. The production of nanostructures, nanocomposites, and modified nanostructures is anticipated to increase because of the need to produce clean water in a more efficient way both with respect to time involved and energy consumption [115].

4. Nanotechnology: areas of concern

The toxic effect of nanoparticles is an area that is the focus of intense scientific research. The chemical and physical properties of particles at the nanoscale are completely different from their properties at the macro scale. It is for this reason that one cannot use the results of toxicity of macro-sized materials to derive the toxic effects of nano-sized particles. Studies point to the fact that smaller the size of the particles, greater is their toxicity. This is due to the fact that surface area of the particles for a given mass increases with the decrease in size of the particles.

There are other complications associated with the fact that nanoparticles in solution tend to aggregate and such aggregates can have properties completely different from individual nanoparticles. More over nanoparticles in powder form or in solution exhibit a range of different sizes, and the toxic effects can differ as the size of the nanoparticles changes. The most commonly studied nanomaterials are CNTs [116–121], TiO_2 [122–124], SiO_2 [125,126], Ag [127,128], ZnO [129], Au [130], AlO_2 [131], nano clays [132], and carbon black [133,134].

It has to be emphasized that most of the techniques employed for the study of toxic effects at the macro level may not be suitable to study the toxic effects at nanoscale.

In view of the limited data available regarding the toxic effects of nanoparticles, regulatory bodies worldwide have not been able to come up with regulations that are specific to nanotechnology, although they agree that nanoparticles constitute potential for an entirely new risk.

5. Conclusion

Lot of research activity is presently going on in different laboratories of the world, both in developed and developing nations with the aim of fabricating cheaper and better nano-products for purification and treatment of water. Some studies have shown the effective use of nanomaterial-based products for the purification of water that meets the WHO guidelines for drinking water. Still more work is required to explore the risks involved with the use of nanoparticles. It is envisaged that in a decade or so, we will see nanotechnology playing a very significant role, especially in less developed nations in providing safe drinking water at cheap rates.

Acknowledgments

The authors gratefully acknowledge the funding provided by the Pakistan Academy of Sciences (PAS). One of us, Ms Saba Imdad, is the Research Associate of the PAS funded Research Project. Most of this work was done at the Preston University, Islamabad and we are very grateful to Dr Abdul Basit, Chancellor of the University for providing excellent facilities and full encouragement. We appreciate the support received from different scientists and experts for their opinions in writing this review.

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