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Nanotechnology for Water Filtration

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Abstract: ***Water scarcity is a pressing issue globally, particularly in regions like the United Arab Emirates (UAE), where arid climates and high population densities exacerbate the challenge. Traditional water purification methods, such as distillation and chlorination, are often inadequate to meet the growing demand for clean water. Nanotechnology offers innovative solutions to address this challenge by leveraging the unique properties of nanomaterials for water purification. In this paper, we explore the potential applications of nanotechnology for water purification within the UAE context, focusing on enhanced desalination, removal of emerging contaminants, treatment of desalination brine, and point - of - use water treatment. By harnessing the power of nanotechnology, the UAE can achieve sustainable and efficient water purification, and thus ensure access to clean and safe drinking water for its population.***

Keywords: water scarcity, UAE, nanotechnology, water purification, desalination

1. Introduction

The skyrocketing population of humanity increases demands for fresh and clean water. With projections estimating the human population to be 9 billion by 2037, the availability of this resource is crucial for survival. Excessive use of pesticides in agriculture, industrialization, and the dumping of toxic waste have deteriorated the quality of over time. Hormones, drugs, cosmetics, industrial products, and microplastics make their way into our water supply chain. Most filtration systems aren't equipped to remove such contaminants, resulting in poor quality of water being supplied to homes. In the 2030 agenda for sustainable development goal 6, SDG6 on water and sanitation, countries have committed to engage and review the sustainable management of water resources, wastewater and ecosystems.

Water scarcity poses a significant challenge for the United Arab Emirates (UAE), where limited freshwater resources and rapid increase in population over the last century strain existing water supply infrastructure. [1] Desalinated seawater and brackish water have become a vital source of freshwater in the country. As of 2017 the UAE had desalination plants with a total of 1.7 billion cubic metres (m^3) per year as installed freshwater production capacity [2]. Not just the UAE, but all of the Gulf Cooperation Council (GCC) countries are heavily dependent on desalination for their freshwater needs. Installed desalination capacity for the GCC region is expected to reach 9 billion m^3 per day by 2030 [3].

Unfortunately, production of desalinated water is both energy - intensive and has significant environmental implications. Desalination plants in the UAE currently use one of two kinds of desalination technologies – thermal and membrane technologies [2].

- Thermal technologies, such as Multi - stage Flash Distillation (MSF) and Multi - Effect Distillation (MED) use heat to separate water from dissolved impurities. These are older and far more energy intensive, using up to 70kWh/ m^3 of freshwater produced [4].
- Membrane technologies, such as Reverse Osmosis (RO) and Electrodialysis (ED) use pressure & thermodynamic phenomena associated with dissolving impurities in water to separate them out of seawater. These newer technologies use much less energy, using upwards of 7 kWh/m^3 [5].

However, current membrane technologies also produce large amounts of discharge brine, which is rich in dissolved salts. Discharge brine is usually released back into the sea, where it has harmful effects on the local flora and fauna, especially corals and sea grasses [2]. This is less of an issue with thermal desalination, which produces smaller quantities of highly concentrated discharge that can be stored on land.

Both these issues – high energy consumption and large environmental impact - underscore the need for alternative water purification technologies. Nanotechnology offers promising solutions for overcoming these challenges by enhancing the efficiency and sustainability of water purification processes. Nanoparticles, with their high surface area - to - volume ratios and unique chemical and physical properties, hold immense potential for revolutionizing water treatment in the UAE. This paper looks at some of the promising technologies on the horizon, and the potential impact they can have on the UAE's water needs.

1) Nano Technology

Nanotechnology is the branch of applied science that comprises the synthesis, engineering, and utilization of materials whose size ranges from 1 to 100 nanometres (nm), known as nanomaterials. [6] Compare this to the average diameter of a single human hair, which is around 80, 000 nm. Their small size gives nanomaterials unique properties compared to materials on a larger scale - at this size range, the macroscale rules of chemistry and physics do not apply. [7] Carbon nanotubes, for example, are six times lighter than steel but have one hundred times greater tensile strength.

Nanotechnology can bring about a paradigm shift in water purification by offering novel approaches to address the limitations of conventional treatment methods. The remarkable properties that nanomaterials exhibit can enable efficient contaminant removal and water treatment. By operating at the nanoscale, these materials can overcome the limitations of traditional filtration and disinfection methods, providing superior performance in terms of removal efficiency, energy consumption, and cost effectiveness. Nanomaterials exhibit enhanced surface area - to - volume ratios, enabling superior adsorption, catalysis, and membrane filtration capabilities [9]. The rest of this section looks at some applications of nanotechnology in water purification:

a) Nano Disinfection

Nano disinfection can remove bacteria and viruses without using harmful chemicals unlike existing disinfection techniques such as chlorination. Silver (Ag) nanoparticles have many advantages over other nanoparticles because they have antibacterial and antifungal properties. [8] Ag nanoparticles are generally smaller than 100 nm and contain 20–15, 000 silver atoms, and have distinct physical, chemical and biological properties compared to silver in its bulk metallic form. Ag nanoparticles kill biological contaminants by destroying the cell wall of bacteria. [9] The Ag nanoparticles induce structural and morphological changes in the bacterial cell, which leads to cell death.

Composite materials impregnated with Ag nanoparticles, which are made using green technology, have shown promising results. [10] Ag nanoparticles have proven their mettle because of their high antimicrobial efficiency and relative cost effectiveness. [11] They can be impregnated on ceramic filters, which can be an effective method of water purification in rural areas where centralized energy and water supply systems may not be feasible. [12] That being said, a meta - analysis of the genotoxicity of Ag nanoparticles, i. e. causing mutations to the genes of animals, was conducted by Fewtrell et al., [13] in 2017. They found no conclusive proof of Ag nanoparticles' genotoxicity, however most studies they analysed showed some evidence of genotoxicity, unless very low dosages of Ag were used. Hence it is prudent to carefully consider the health and environmental impact before deploying solutions based on Ag nanoparticles at a national scale.

b) Photocatalysis

Photocatalysis is the process of changing the rate of a reaction using catalytic materials that are activated by light [14]. The substrate that absorbs light and acts as a catalyst for chemical reactions is known as a photocatalyst, and it is usually composed of a semiconductor, most commonly Titanium dioxide (TiO_2) [15]. The principle of photocatalysis is based on the excitation of a semiconductor by light (UV or visible). With incident radiation of proper energy (*hv*) that is equal to or greater than the bandgap energy of a photocatalyst, an electron in the valence band (VB) is transferred into the conduction band (CB) level, with the formation of a hole in the VB. The excited electron and photogenerated holes play a critical role in photocatalytic degradation of organic pollutants. Under the action of photons, the semiconductor (or catalyst) produces highly oxidizing free radicals allowing the decomposition of compounds adsorbed on its surface. [16] Photocatalysts hold great promise, not only for purifying water for consumption, but also in the treatment of wastewater before it is released into the environment. Domestic sewage is especially rich in synthetic organic compounds and pathogens that can be harmful to the environment.

Nano - catalysts are very effective against pathogens like E. coli and against pharmaceuticals compounds. [17] When the nano particles are activated by UV light, they break down the pollutants into non - toxic by - products, but they themselves remain unchanged. Hence, they can be collected and re - used. As mentioned earlier, the most commonly used nano particle for UV photo - catalysis is TiO_2 because it is stable, non - toxic and low cost [18]. The major drawback is the fast recombination rate of photo generated charges, which limits its large - scale application. To overcome this, scientists are researching composites with graphene [19], a unique form of carbon with interesting electromagnetic and chemical properties.

c) Nano Adsorption

Adsorption is the capability of solid substances to attract dissolved molecules out of fluid mixtures (liquid or gas) and reversibly adhere them on to the surface of the solid. Solids that are used to adsorb gases or dissolved substances are called adsorbents.

Nano adsorbents are molecules with unsaturated surface atoms and hence can attract other element ions (heavy metal ions/ water contaminants) by static electricity, which get attached to their surface. [20] Afterwards, thess nano adsorbents bearing toxic ions can be removed and discarded. Nanomaterials can strongly adsorb trace metals and polar organic compounds. Common heavy metals like lead (Pb) (II), Nickel (Ni) (II), Zinc (Zn) (II), Copper (Cu) (II), Cadmium (Cd) (II), Chromium (Ch) (IV) can be filtered using nano adsorbents. Due to their high surface area ratio nano adsorbents have a large number of sites for the adsorption of contaminants, and therefore show a high rate of adsorption. This process also allows the development of smaller and more compact water purification devices. Some of the adsorbents under research are carbon nanotubes (CNT), polymeric nano adsorbents, zeolites, and metal - based nano adsorbents. Schematic structures of these materials are shown in Figure 1:

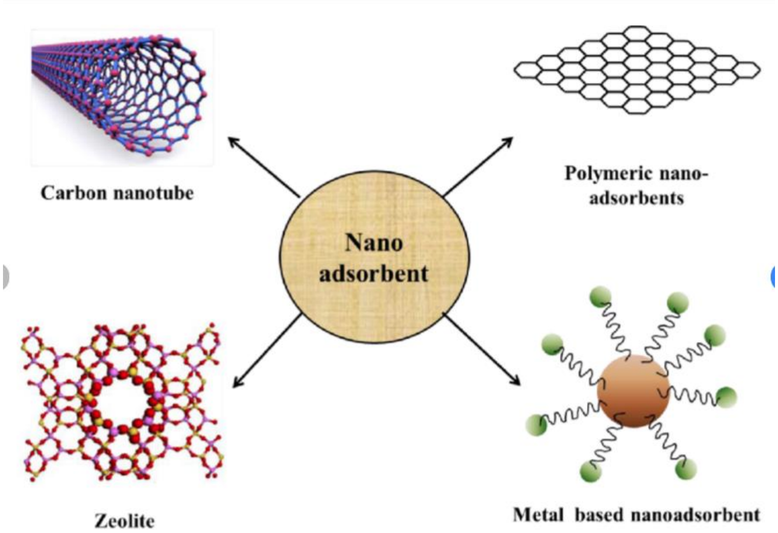

Figure 1: Four promising new categories of nano adsorbents:

2) Carbon Nanotubes (CNT)

Carbon nanotubes (CNTs) are cylindrical molecules that consist of rolled - up sheets of single - layer carbon atoms (graphene). They can be single - walled (SWCNT) with a diameter of less than 1 nanometer (nm) or multi - walled (MWCNT), consisting of several concentrically interlinked nanotubes [21].

The adsorption process in case of CNTs is usually controlled by four possible active sites: (i) the hollow interior of individual CNT designated as internal sites; (ii) the interstitial channels between CNT in the stacks; (iii) the grooves between adjacent CNT; and (iv) the external surface of individual CNT. [17]

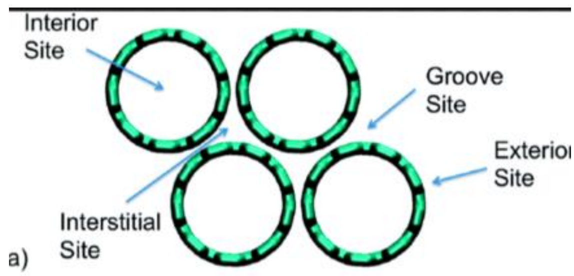

Figure 2: Structure of Single Wall Carbon Nanotubes (SWCNT) showing sites for adsorption

Studies have shown that higher ionic radii of heavy metals reduce adsorption capacity. Metal ions with higher electronegativity have stronger adsorption. However, the problem with CNT is when bundled, their specific area for adsorption decreases. [22] CNTs can also leak into the water supply and their effect on humans and environment is not yet completely researched.

a) Graphene Based

Graphene is a unique form of carbon which consists of carbon atoms bonded in six - member rings along a flat plane layer, and can consist of up to 10 such layers held together by electromagnetic forces [23]. Graphene family based layered nano materials include Graphene Oxide (GO), reduced graphene oxide (rGO), few layer graphene and ultra - thin graphene. [24] Touted as the wonder material of the future, it has diverse applications ranging from bionic devices, solar panels, batteries, cancer treatment, gene delivery. Several functional groups can be bound to the carbon plane, e. g., hydroxyl, carboxyl, and epoxide, and serve as the active sites for the removal of metallic ions from water. These sites have high negative charge densities, which result in their strong interactions with positively charged metal ions for their removal. The idea of using graphene is not new, but the technique is still expensive to be exploited on an industrial scale. The other issue limiting factor is health and environmental risk due to leeching of these materials in water. [25]

b) Silica Based

Silica (or Silicon dioxide, SiO_2) is a naturally occurring compound which is found in many crystalline and amorphous forms, many of which have unique properties. According to the IUPAC system, mesoporous silica nanoparticles (MSNs) structures are classified as particles with pore sizes of 2–50 nm and functionalized with different supplementary groups. [26]. These nanocarriers can be prepared in a variety of sizes and shapes including nanohelices, nanotubes, nanozigzags, and nanoribbons. The mesoporous silica nanoparticles show some toxicity above tolerance levels. [27] Si - O - Si bond shows poor stability in basic condition, which may cause the leaching of the surface grafted functional groups.

c) Nanoscale Zero - valent Iron (nZVI)

Nanoscale zero - valent iron (nZVI) is particulate metallic iron with a particle size of less than 1 µm. nZVI primarily consists of an Fe core coated in an iron (hydro) oxide shell, with a specific surface area that is typically greater than 20 $m^2 \cdot g^{-1}$. [28] Commercially it is available in the form of uncoated, iron oxide coated and organic coated. They are non - toxic, abundantly available in nature, cheap and easy to produce. It is a good adsorbing and reducing agent. Heavy metals like cadmium, chromium, and lead can be adsorbed on these nanoparticles and can be converted into less toxic form. [29] Due to higher specific area, more pollutants can be removed; however, nZVI oxidises in air and aqueous solutions (similar to rusting in bulk iron), which results in slowdown in reduction process of heavy metal ions.

d) Magnetic nano particles

Magnetic nanoparticles are a class of nanomaterials composed of metals such as cobalt, nickel and iron with paramagnetic, ferromagnetic or superparamagnetic properties. The major advantage with magnetic nanomaterials lies in their easy recovery after exhaustion from the treated solution by applying an external magnetic field. Nanoparticles without magnetic properties have limited applicability in water purification due to the difficulty of separation from the aqueous solution [30]. Magnetic nanoparticles present advantages due to their large surface area, size, and shape - dependent catalytic properties and can be separated from the aqueous solution with the use of a magnet field [30] However, the use of magnetic nanoparticles, which provide larger removal capacity, higher reactivity, high surface - area - to - volume ratio, high degree of dispersion, excellent adsorption affinity, and catalytic activity [31], also presents a challenge in terms of recovery, stability, and toxicity. In chemical terms, iron oxide nanoparticles can be oxidized in air, similar to nZVI, resulting in the loss of dispersibility and magnetism [32].

e) Zeolites

Zeolites are nano - porous aluminosilicates with a 3D porous structure and are used for disinfection. These come in various classes based on pore sizes. Micro pores (<2nm), Meso pores (2 - 50nm) and Macro pores (>50nm). [33] Various factors such as pH, temperature, dose and contact time influence the absorption of heavy metals when using zeolites. The modification of zeolite with various materials enhances its adsorption capacity. Zeolites have a very porous structure which help them adsorb volatile organic compounds and gas molecules. Specific zeolites help in getting rid of specific impurities. For example, clinoptilolite is used for removing ammonia, and chabazite is effective at removing heavy metals. [34, 35] Ion exchange is one of the primary mechanisms for removing contaminants. Zeolites have a negative charged framework which exchanges positively charged cations present in water. Heavy metals like Pb and Cd are exchanged by less harmful ions like calcium and sodium. Zeolites are packed in columns through which water flows for purification. The packing density and particle size of zeolites are a crucial factor to consider for determining efficiency. This makes purification cost - effective.

f) Polymeric based

Polymeric nanoparticles (PNPs) are a mix of biocompatible, nontoxic, and biodegradable polymers with synthetic or natural origin, which can be either nanospheres or nano capsule types. They can be made from either carbon or graphene or metal organic frameworks (MOFs) or natural origins like cellulose, alginate and chitosan [36]. They are made of tailor - made external branches which can adsorb heavy metals and inner hydrophobic shells that can absorb organic compounds. They have very good stability over a range of pH and can link to both bases and acids.

3) Nano Filtration

Nano filtration uses nano membranes, which are thin, typically less than 100nm selectively permeable membranes. These nano - membranes can filter out bacteria, viruses and pesticides. due to their small pore size. However, due to smaller pore size, the pressure and energy required to push water through the membranes increases. [37] In terms of selectivity, nano filtration falls between reverse osmosis (which only allows the passage of water, but is relatively very energy intensive) and ultrafiltration (which uses less energy, but allows the passage of viruses and organic macromolecules).

Like all membrane - based systems, nano filtration is also affected by fouling. Fouling is the deposition of suspended or dissolved substances on a membrane's external surfaces, pore openings or within its pores, which results in the loss of performance of the membrane. Fouling is an irreversible and time - dependent phenomenon; it is related to the characteristics of the membrane and solute - solute and solute - membrane interactions that cause an irreversible decline in the flow of permeate, which can only be recovered by the chemical cleaning of the membrane. [38]

II. Nanotechnology for UAE

Due to almost non - existent fresh - water resources available in its arid desert climate, UAE must rely on desalination plants for fresh water. Desalination can be carried out by thermal or membrane process (Reverse Osmosis). In UAE due to large scale availability of petroleum products for energy generation, thermal desalination methods such as multi - stage flash distillation (MSF) and multi - effect distillation (MED) are used. [4]

In MSF sea water is heated and then passed through series of chambers with reduced pressure. With reduced pressure, the boiling point of water also reduces and water flashes into steam. The steam is then condensed to produce fresh water, while the remaining brine is discarded. In MED, seawater is heated in multiple chambers or effects, each at successively lower pressures. As the water flows through each effect, it evaporates and condenses on the tubes or plates carrying a heat transfer fluid. The heat from the condensation process is then used to evaporate water in the next effect, thus utilizing the heat efficiently.

Newer desalination plants in the country use Reverse Osmosis (RO). RO uses a special membrane which blocks the passage of dissolved salts and other impurities as seawater is forced through at high pressure. The output is freshwater with a very low amount of dissolved salts, and a byproduct is brine which is rich in salts and impurities. RO based plants require powerful pumps to generate high pressures to ensure pure water is extracted. [5]

Graphene - based Nanomembrane

Mohsen et al. [39] tested water obtained via desalination using graphene composites. The results indicate that the obtained water is totally pure and free from all salts, metal ions and heavy metals. [39] Different techniques are used to produce graphene like epitaxial growth, liquid phase exfoliation, electrochemical exfoliation, mechanical exfoliation, and chemical vapor deposition are used for graphene. [40] However current methods of pure graphene production are expensive, around USD 200 per kg. Much research is ongoing to reduce this cost and enable mass production.

In 2021, the Indian Institute of Technology Patna developed a way to produce graphene using plasma gun, without the use of chemicals. [41] Researchers at MIT and Harvard University are exploiting graphene oxide, imperfect as soiled with atoms of oxygen and hydrogen, but cheaper than the pure material. From graphene oxide and using ultrasonic techniques, they produced nano scrolls of controllable dimensions. Nano scrolls are developed with the same mechanical properties as graphene for only a fraction of its cost. [42]

Enhanced Desalination

Traditional desalination methods described above, such as MSF, MED & RO, are energy - intensive and costly. Nanotechnology offers a pathway to enhance the efficiency of desalination processes through the development of nanocomposite membranes. These membranes, incorporating nanoparticles into their structure, exhibit improved water permeability and salt rejection properties, leading to higher freshwater production rates and lower energy consumption. Table 1 illustrates the relative energy consumption of conventional RO desalination and the potential reduction achievable through nanocomposite membranes.

Table 1: Comparison of Energy Consumption in Desalination Methods

**Desalination Method	Energy Consumption (kWh/m^3) **
Conventional RO (Low efficiency)	8.5 [4]
Conventional RO (High efficiency)	6.5 [4]
RO with Nanocomposite Membrane (Estimated improvement)	5.0 [4]
Multi - Stage Flash (MSF) Desalination (Thermal)	70 - 90 [5]
Multi - Effect Distillation (MED) Desalination (Thermal)	45 - 60 [5]

Notes:

- This dataset incorporates a range for conventional RO to account for variations in efficiency depending on factors like plant design and operation.
- It includes thermal desalination methods (MSF and MED) for comparison, though the focus of the paper is on RO advancements.
- The data for nanocomposite membranes is an estimate based on potential improvements over conventional RO. Actual figures may vary depending on the specific technology and implementation.

The table above compares the energy consumption (kWh/m^3 of freshwater) of conventional RO desalination with the potential reduction achievable through nanocomposite membranes. It can be seen that the integration of nanocomposite membranes into the RO desalination process results in a significant reduction in energy consumption, highlighting the potential of nanotechnology to enhance the efficiency of desalination operations in the UAE.

Removal of Emerging Contaminants (ECs)

Emerging contaminants (ECs) refers to synthetic compounds that are entering ecosystems in increasing quantities and posing unique challenges to environmental conservation. These include pharmaceuticals and microplastics. ECs pose a growing threat to water quality and public health.

Conventional methods to remove ECs include RO, filtration, and usage of oxidising agents such as chlorine. However, these methods are either not sufficiently efficient at removing ECs (filtration), require significant amounts of energy (RO), or produce undesirable byproducts (oxidants). Yet, at present, waste water treatment plants continue to use a combination of the above methods.

Effective and efficient treatment of waste water is particularly important to the UAE. In 2017, the country generated roughly 500 million m^3 of wastewater, of which about 289 million m^3 was treated and 248 million m^3 was reused [43]. For context, the amount of wastewater generated was a little less than 30% of the total installed desalination capacity in the UAE that year, as mentioned in the introduction. Repurposing wastewater to the extent possible will go a long way towards meeting the UAE's water needs.

Nanomaterial based treatment systems are proving to be more energy efficient while also removing ECs from wastewater effectively and without creating undesirable byproducts. Many of the nano adsorbents discussed above are being tested for this purpose.

2. Prospects

Nanotechnology has the potential to revolutionize water treatment. Using nano technology, point - of - use water purification systems using renewable energy like solar energy can be designed. Solar powered reverse osmosis (RO) systems can be designed. Solar energy can be used to fuel the distillation process in solar - powered RO desalination. Solar energy is gathered using photovoltaic panels (PV) and stored in batteries and reverse osmosis desalination can be driven by it. The batteries shall be designed to store sufficient solar energy, to ensure continuity during nighttime. This method can be useful for remote areas, where the water requirement is moderate.

Another alternative is to use wind energy to power desalination plants. UAE has many oil and gas processing offshore platforms. An offshore platform is a large structure with facilities for well drilling to extract, store and process petroleum and natural gas, built in sea. Windmills can be built along these platforms, where wind speeds are high. The water obtained from these wind - powered desalination plants (installed on platform) can be utilized for personnel working on the platforms. This will save the transportation cost incurred to supply fresh water to these platforms using Offshore Supply Vessels [44].

Sea waves powered desalination plants can be a possibility in UAE. Floating buoys tethered to ocean floor can use wave power (tidal power) to drive a pump that forces seawater through filters and reverse osmosis membranes. The fresh water can then be piped ashore again powered by the natural motion of waves.

Replicating the lab results in commercial production is still the biggest challenge, however with the advancing technologies, nanotechnology can soon be utilized on large scale water treatment and purification. It is also imperative to study the biological impact and toxicity of these nanoparticles.

3. Conclusion

Nanomaterials have unique properties, as compared to their bulk counterparts. Combining nanotechnology with green energy can benefit the environment. Photocatalysis powered by solar energy can be carried out by using nanostructures. Nanofiltration using membranes can convert hard water into soft water by removing heavy metal ions as it passes through the semi permeable membranes. Solar powered RO desalination plants can be designed to utilize renewable energy and thereby reduce carbon footprint. Simple solar operated devices such as solar stills and solar - assisted distillation systems can be used. Wind - Powered and Wave - Powered RO desalination plants need to be further researched for their optimal utilisation. Combining Renewable Energy with emerging nano technology can be win - win for growth, economy, and environment. Continued research, investment, and collaboration are essential to unlock the full potential of nanotechnology for sustainable water management in the UAE and beyond.

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