**Nanotechnology in Water Treatment**

**What is Nanotechnology?**

Nanotechnology is a rapidly evolving field of science that operates at the nanoscale, manipulating matter at a size of 1 to 100 nanometers (NIOSH) . This manipulation of atoms and molecules enhances the properties of certain compounds, creating more robust and more reactive materials, known formally as nanomaterials. Nanomaterials are substances with drastically different properties than their larger particulate counterparts, caused by macroscopic quantum effects, such as changes in a material's solubility, reactivity, conductivity, and permeability. Though there has not been a large-scale adoption of nanotechnology, many applications exist in medicine, consumer products, energy, materials, and manufacturing.

**The Importance of Water**

Water is vital in day-to-day tasks, manufacturing and agriculture. Globally, nearly two billion people use unclean or contaminated drinking sources. Close to a million deaths every year in low and middle-income countries are due to inadequate drinking water (WHO). A vast majority of children under five are adversely affected by poor water quality. Poor water and sanitation conditions account for approximately 80% of worldwide illnesses (Canada, Global Affairs). Most of North Africa and nearly half of European countries, which account for about 70 percent of the population, lack proper water supply. The demand for freshwater is also drastically growing, especially with the increase in the global population. Over 70 percent of the world's freshwater is used for agricultural irrigation in developed and developing countries (Montgomery, 2007).

**Current Water Treatment Methods**

Current large- and small-scale water treatment plans require many moving parts and constant surveillance and maintenance. The general treatment plan used in large-scale purification follows the process of some form of coagulation, flocculation, chemical treatment and filtration. Coagulation combines fine particles and pollutants to be later filtered out in flocculation (Bonnett, 2023). This stage causes the reduction in total organic carbon and absorbable organic halogens and prevents bacterial growth. However, this process requires disposable chemicals and does not effectively reduce arsenic content. Long term exposure to arsenic can cause cancer and skin lesions. In the filtration process, activated carbon is an effective tool for eliminating many chemicals and compounds in water. It efficiently removes bioorganisms that require oxygen, suspended solids and colour from water (Alves et al., 2021). Activated carbon is relatively expensive and difficult to reuse, resulting in commonly occurring material loss. It is a non-destructive and non-selective process, meaning certain viruses and bacteria can still pass through the filtering process, as well as particular dyes and metals.

Chemical oxidation is another common water treatment method, which uses chemical compounds such as chlorine or ozone. Chemical oxidation is simple, rapid, and efficient; good at reducing pollution, colour, and effective for the treatment of cyanide and sulphide removal. However, chemical oxidation produces organic volatile compounds, which can cause damage to the nervous and immune systems, especially in younger children (Oregon). Moreover, producing, transmitting, and managing these oxidants is challenging as they have a short lifespan. Certain compounds like chlorine have adverse effects pertaining to long-term use, such as cancer and other diseases. Many developing countries use activated carbon, sand filtration, and chemical oxidation to treat their water, as they are relatively more accessible and does not require proper infrastructure to work effectively.(Crini et al., 2019).

Reverse Osmosis membranes are a nanomaterials commercially available for water treatment . There are no chemicals, and it produces little waste. It efficiently eliminates particles, suspended solids and microorganisms, volatile and nonvolatile organisms, phenols, cyanide and zinc. It can be metal selective and can be used in a wide variety of real-world applications, such as sterile filtration, desalination and production of pure water. Reverse Osmosis(RO) has high maintenance and operation costs. The costs are too high for small and medium applications, and the choice of membrane is determined for specific applications. Water filtered through RO is demineralized and slightly acidic, and the process does not remove volatile organic compounds (VOCs) (Hearn, 2015).  With prolonged consumption, mineral imbalance can cause gastrointestinal and kidney problems (Oregon). The buildup of VOCs in the human body can also cause eye, nose, and throat irritation or damage to the liver, kidneys, or nervous system.

The use and application of nanotechnology in improving water quality would provide low-income countries with better and more effective waste treatment plans to eliminate many causes of disease. Nanotechnology can also be implemented in large-scale applications, becoming the supporting infrastructure of the future.

**Application of Nanomaterials in Water Treatment**

Nanotechnology can create highly modular and multi-functional systems for affordable water treatment that rely less on large-scale machines and infrastructure. Nanomaterials feature a variety of applications, including varying nanotube and membrane solutions for preventing microbial growth and the flow of particulates. Carbon Nanotubes, (CNTs), have higher efficiency than activated carbon in absorbing certain organic chemicals (Xiaolei et al., 2012). The high efficiency is a result of its large internal surface area and ability to interact with particular objects. CNT is made out of graphene, and other materials are very good at absorbing solid acids and oxidizers. It has remarkable mechanical strength and can make robust, long-lasting membranes (Bodzek et al., 2019). Metal-based nanotubes are also very efficient and suitable for the absorbency of heavy metals and radionuclides (Xiaolei et al., 2012). The nanocrystals can be compressed into porous pellets and still be equally effective, allowing them to be flexible for various applications. They have higher adsorption capabilities because of the numerous surface reaction sites (corners and edges).

Additionally, denser nanometal filtrations are more effective at removing arsenic from its environment. It also has superparamagnetic properties that trap certain metal particles. Nanomaterial membranes are commonly used as physical barriers for stopping particles based on their size. Reverse osmosis is an aforementioned example of a membrane, but other membrane solutions, such as forward osmosis or nanocomposite membranes, can also serve as replacements and improvements. Nanocomposite membranes are made of metal-oxide nanoparticles, which are long-lasting and have high permeability. Forward Osmosis, another nanomaterial membrane process, has all the benefits of reverse osmosis but does not require high pressure for treatment and has a longer lifespan. These nanomaterial membranes can be easily automated and require less land and chemical use. It can easily be incorporated into any water treatment design, both on a small scale and a large scale.

Nanotechnology is also used to track and remove viruses. Nanoparticle-based biome sensors could detect the presence of COVID-19 in wastewater. Doped carbon nanoparticles can find SARS-CoV markers, a possible cost-effective method for detecting the COVID-19 virus. Specific nanomaterials, such as silver and gold, can destroy a virus' membrane and limit replication. These nanomaterials reduce microbial growth with their unique antibacterial properties, such as generating reactive oxygen species, which can kill viruses and their supporting cell components(Al-Hazmi et al.,2023).

**Challenges in Developing Nanotechnology for Water Treatment**

While promising, the current applications of nanotechnology in water treatment are still in the early stages of testing and research. The potential risks of widespread use, particularly the effects of nanomaterials and nanoparticles on the environment, ecosystems, and human health, still need to be fully understood.

Recent studies have shown that human physiology can be affected by specific metal nanoparticles in water treatment. The reactivity of nanoparticles in water causes the production of reactive oxygen species (ROS). ROS are unstable molecules that contain oxygen and can quickly react with other cell molecules(NCI, 2024). An influx of nanomaterials into the body through ingestion or inhalation can lead to a buildup of ROS. Oxidative stress from ROS can cause inflammation and weaken immunity, damaging DNA and other proteins. Researchers focused on the respiratory exposure of nanomaterials in rodents and analyzed lung injury, cell mutation, and ROS, causing additional problems to their tissue (Theron, 2008).

High concentrations of nanomaterials can also lead to environmental and biological pollution. Research has shown that nanometals affect aquatic ecosystems in various ways.Certain nanometals, such as titanium dioxide (TiO2), can affect algae, invertebrates, fish and aquatic plants. The (TiO2) causes respiratory stress and diseases that affect the gills and intestines (Gehrke et al., 2015). Experiments performed on plants also show increased cell death, difficulties in germination and the production of toxic seeds (Hemalatha et al.).

CNTs are considered a potential upgrade to activated carbon in many filtration systems, but they are unsuitable for wide-spectrum absorption as they are better for targeting specific hydrocarbons (Xiaolei et al., 2012). Additionally, CNTs can unnecessarily bond with certain polar compounds, such as alcohols, hindering the filtration of contaminants.

The cost and feasibility of manufacturing nanomaterials might make it difficult for commercial use in the coming years, especially for implementation in low-income countries. However, the reusability of nanomaterials and membranes in water treatment can make it easier to establish water treatment systems using nanotech in low-income countries in the long run. Setting up high-quality water treatment systems is expensive due to the initial investment in infrastructure. Nanomaterials can provide the same efficiency, quality, and reliability level as an industrial water treatment of 1000ths of the size.

To advance our understanding of nanotechnology in water treatment, it is crucial to shift our focus from small-scale lab testing to comprehensive large-scale field testing. This will provide a more accurate assessment of its efficacy, long-term impact on ecological systems, and potential effects on human health.

Casting these parameters in the real world would be essential and valuable, and many tests have been done on small animals, such as rodents, to help determine the scale of the impact it can have—additionally, shifting away from testing and implementing expensive, complex solutions. Industries companies and researchers should shift their focus towards helping low-income countries.

**Evidence Based Recommendations**

Shifting away from testing and implementing expensive, complex solutions. Industries companies and researchers should shift their focus toward helping low-income countries and impoverished areas. By shifting to areas with high levels of famine and lack of proper healthcare, funding from NGOs and companies can improve their quality of life by giving them good water quality and understanding the long-term efficacy of the nanomaterials.

At this stage, underdeveloped countries present a unique opportunity for the application of nanotechnology in water treatment. Unlike first-world countries with established water treatment systems designed to last about a hundred years or more, these underdeveloped regions are more open to innovative solutions. This makes them ideal for the implementation of nanotechnology-based solutions.

Lastly, investment in further research into nanomaterials and nanometals is essential to help understand the best possible tool for water treatment forward, and future advancements can help reduce its cost of production, manufacturing and recycling. Forward Osmosis shows promise as an effective nanomaterial membrane for water treatment. It could easily replace the currently reverse osmosis membranes and be commercially sold cheaper, as the mechanism requires less precision to work effectively.

**Conclusion**

In the past few years, advancements in nanotechnology have provided a renewed focus on revolutionary water treatment methods. Improvements to global water quality can help combat disease, famine and water scarcity—though practical, current water treatment methods feature many flaws and require many perishable and non-renewable materials. Even though the future of the technology is promising, the toxicity of specific nanomaterials means that a commercially ready product must be safe for the environment and human health. Its use in established countries soon might be complex, but nanomaterials would vastly improve impoverished areas.

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