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Nanotechnology Use in Water Purification for Sustainable Development of Middle East

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Abstract

Growing world population and increasing demands have put considerable pressure on natural resources and the environment. As a result of this situation, the Sustainable Development Goals (SDGs) have been established to safeguard rights and ensure that everyone's fundamental needs are met by 2030. It is one of the goals of the program to ensure that clean water and sanitation are accessible to all. In this review, we focus on the water crisis in the Middle East, a region with limited water resources and a growing population. The use of nanotechnology as a transformative solution for water purification and sanitation is proposed in this paper. In addition to addressing the water challenges in the Middle East, this technology can also contribute to the achievement of the Sustainable Development Goals' vision of providing universal, affordable, and sustainable access to clean water.

Keywords: Nanotechnology; Water Purification; Sanitation; Sustainable Development; Middle East

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استخدام تقنية النانو في تنقية المياه من أجل التنمية المستدامة في الشرق الأوسط

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ملخص

يؤدي العدد المتزايد من البشر وأنشطتهم في جميع أنحاء العالم إلى زيادة الطلب العالمي على السلع الأساسية والتأثير على بيئة الأرض العالمية ومناخها. تتضمن أهداف التنمية المستدامة(SDGs) حقوق الإنسان للجميع من أجل الضروريات الأساسية في الحياة والتأكد من توفر الحقوق الأساسية بحلول عام 2030 للجميع. أحد أهداف التنمية المستدامة هو وصول مصادر المياه والصرف الصحي لجميع الناس. في هذا البحث، نعرض الوضع المائي في الشرق الأوسط، ونعرض الحلول المقترحة من خلال استخدام تقنية النانو في تنقية وتعقيم المياه لتنفيذ رؤية المياه النظيفة المستدامة الميسورة التكلفة لمنطقة الشرق الأوسط بشكل عام ولجميع الناس.

الكلمات المفتاحية: التكنولوجيا النانوية، تنقية المياه، الصرف الصحي، التنمية المستدامة، الشرق الأوسط

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1. Introduction

In recent times, the global population has seen an exponential increase. The United Nations estimated in 1915, that the worldwide population stood at about 1.8 billion people (Teo et al., 2021). Today, it has surged to approximately 7.3 billion and is projected to reach 9.7 billion by 2050 (Schierhorn, 2016). Such growth amplifies global demands for essential commodities, magnifying the human footprint on earth's environment and climate (Chopra et al., 2022).

Recognizing the importance of addressing these challenges, the United Nations members established the Sustainable Development Goals (SDGs) in 2015. These goals, a part of the United Nation's 2030 Agenda for Sustainable Development, ambitiously aim to eradicate poverty, promote sustainable and inclusive development, uphold human rights, and ensure no one is marginalized by 2030. They underscore the interconnectedness of actions across regions, advocating for a balance between social, economic, and environmental sustainability. Encompassing 17 objectives, the SDGs target advancements for the welfare of people, the planet, and prosperity (Murphy et al., 2006).

However, not all challenges are solely due to population growth. The United States Agency for International Development (USAID) highlights that the global "water crisis" stems not just from scarcity but from inadequate management and inequitable distribution, and, it's not only the developing nations that grapple with this issue (World Bank, 2017). Nations such as Ethiopia, Nigeria, Somalia, South Sudan, and Yemen face acute drought conditions and conflict-induced water shortages. Distressingly, UNICEF predicts that, by 2022, over 9 million individuals in Ethiopia will lack access to safe drinking water (Kwami et al., 2019). Moreover, almost 1.4 million children in South Sudan, Nigeria, Somalia, and Yemen are at severe risk due to acute malnutrition (Courtene et al., 2017).

In the face of these challenges, the potential of creativity, innovation, technology, and financial resources is undeniable. Nanotechnology, especially, holds immense promise. Referring to tools, techniques, and applications involving particles sized from a few to hundreds of nanometers in diameter, nanoparticles display unique physicochemical and surface properties (Prajapati et al., 2013). Their utility spans across industries such as electronics, health monitoring, and renewable energy – particularly in sunlight conversion for solar panels and energy storage in batteries to mitigate climate change (Gratzel et al., 2009).

Given the mounting global interest, investments in nanotechnology have soared. For instance, Japan's investment multiplied six-fold from 1997, reaching US $750 million by 2002 (Sun et al., 2009). The Middle East, grappling with challenges like poverty, conflict, and inadequate infrastructure leading to water contamination, stands to gain significantly from embracing nanotechnology (Briceno et al., 2004). With a robust technical foundation and a vast population, the region is ripe for research and development in this domain (Rios et al., 2009).

One specific application is nanotechnology water filtration, which employs minute particles, less than 100 nanometers in size, to purify water (Ahmed et al., 2014). Comprising materials like titanium dioxide nanoparticles, carbon nanotubes, and activated charcoal, these filters are not only effective but also safe for human consumption (Ali et al., 2020; Sekhon et al., 2014). They also present an alternative to traditional chlorine-based disinfection systems, efficiently eliminating bacteria and viruses from drinking water supplies (Mauter et al., 2018). Moreover, unchecked bacterial, fungal, and algal growth in water sources, which use pollutants for sustenance, can exacerbate water toxicity. Such overgrowth increases ammonium levels, depleting oxygen in water (Hairom et al., 2021). High nitrogen concentrations compromise water quality, affecting human health, aquatic life, and local economies (Camargo et al., 2005; Camardo et al., 2003).

This research underscores the potential of nanotechnology in addressing water challenges, especially in removing contaminants like heavy metals. Moreover, in regions like the Middle East, nanotechnology can harness water molecules from atmospheric humidity. Given that many Middle Eastern nations are coastal, this technology is particularly relevant. However, it is essential to note that even inland areas, including deserts, contain suspended water molecules in the atmosphere.

2. Methods

Although conventional methods exist for nitrogen removal in water, they often fall short in meeting the criteria for environmental discharges. For example, gravity flow systems are limited in their application, particularly on steep terrains (Wu et al., 1995). Additionally, when microflows conglomerate into visible colloids, they can generate hazardous substances (Kharal et al., 1998). Biological and ecological methods, influenced by factors such as temperature and seasonal changes, demand extended durations to effectively treat polluted water.

Currently, desalination fulfills only a small portion of human water needs, primarily due to its higher costs compared to alternative water sources. This process involves converting saline water, often seawater, into fresh water. The two primary techniques employed for desalination are reverse osmosis and distillation. Each of these methods has its own set of advantages and limitations.

Reverse osmosis is a membrane-based method, whereas thermal methods include multistage flash distillation (Panagopoulos et al., 2019). The traditional desalination method involves distillation—boiling and then re-condensing seawater to extract salts and impurities (Bohulu et al., 2019). Currently, reverse osmosis and multi-stage flash distillation dominate in terms of global desalination capacity (Do Thi et al., 2021). In arid regions, economic feasibility for desalination is typically reserved for high-value uses, such as residential and industrial purposes.

However, desalination for agricultural purposes is gaining traction, especially in densely populated areas like Singapore and California. The process is most extensively used in the Persian Gulf (Le Quesne et al., 2021). Various techniques employed in water treatment include ultrafiltration, crystallization, sedimentation, gravity separation, flotation, precipitation, coagulation, oxidation, solvent extraction, evaporation, distillation, reverse osmosis, ion exchange, electrodialysis, electrolysis, adsorption, setting-out, centrifugal and membrane separation, fluidization, neutralization, remineralization, reduction, oxidation, and more.

The chosen technique often depends on the nature of the water contamination and its intended purpose (Stackelberg et al., 2004). While these methods are effective, the presence of contemporary anthropogenic pollutants, linked to modern human activities, complicates the water purification process.

In this context, nanotechnology emerges as a promising solution. Technologies powered by nanotechnology offer high-performance, cost-effective solutions for water and wastewater treatments, attributable to their efficiency, versatility, and multifunctionality. Materials constructed with nano-objects possess strength and a vast specific surface area (SBET), ensuring a high surface-to-volume ratio that facilitates better contact with contaminants and/or microorganisms (Qu et al., 2013). However, integrating nanotechnology into water treatment technologies also presents substantial challenges to existing methods.

Major Limitations Associated with Conventional Water Purification Methods

Conventional Methods	Limitations
Distillation	Most contaminants remain behind and require high amounts of energy and water. Pollutants with boiling point >100°C are difficult to remove
Chemical transformation	Excess reagents are required. Product may be a low-quality mixture and cannot be released into environment. Inactive in harsh conditions. This is not highly selective method
Coagulation and flocculation	This is a complex and less-efficient method and requires alkaline additives to achieve optimum pH
Biological treatment	Microorganisms are sensitive to environmental factors and difficult to control. Intermediates damage the microbial cells. This is not cost effective. Time consuming
Ultraviolet treatment	Expensive method and inactivated by water cloudiness and turbidity. Ineffective for heavy metals and other nonliving contaminants removal
Reverse osmosis	This method removes minerals from water which is unhealthy, and the treated water will be acidic. This method cannot remove volatile organics, chemicals, chlorine, chloramines and pharmaceuticals. Requires high energy
Nanofilteration	This technique requires high energy, and pretreatment. Limited retention for salts and univalent ions. Membrane fouling will occur with limited lifetime and expensive
Ultrafiltration	This method will not remove dissolved inorganics. Requires high energy. Susceptible to particulate plugging and difficult to clean
Microfiltration	Cannot remove nitrates, fluoride, metals, sodium, volatile organics, color, and so on. Requires regular cleaning. Membrane fouling will occur. Less sensitive to microbes, especially virus
Carbon filter	Cannot remove nitrates, fluoride, metals, sodium, and so on. Clogging occurs with undissolved solids. Susceptible to mold. Requires frequent changing of filters

* From: Kunduru et al., Chapter 2017.

Nanotechnology holds considerable promise for economically filtering and harnessing non-traditional water sources.

It is essential to emphasize that nanomaterials used for water purification should be environmentally friendly and non-toxic. If unsafe nanoparticles interact with the human body, they can pose significant threats to vital organs. Due to the dimensional properties of nano-objects, there is potential for them to move to different organs, heightening the possibility of biological harm. Hence, before integrating these nanomaterials into the industry, comprehensive safety data sheets, standard operating procedures (SOPs), and other pertinent regulatory documents must be in place, detailing toxicity performance assessments.

A membrane is a thin, porous layer that allows water molecules to pass through but restricts the movement of salts, metals, pathogens, and viruses. Membrane operation can be driven by either electrical forces or pressure. Pressure-driven membrane technology can purify water to virtually any level of desired purity (Kumar et al., 2014). The sophistication of water and wastewater treatment using membrane separation techniques continues to grow. Membranes, based on their pore and molecular sizes, differentiate and segregate various substances. This makes membrane separation a reliable and automated approach to wastewater treatment (Gehrke et al., 2015).

3. Nanofiber Membranes

Electrospinning offers an easy, cost-effective, and efficient method to produce nanofibers. The resulting nanofibers boast a high porosity, expansive surface area, and intricately woven pore patterns. The physical and chemical attributes of electrospun nanofibers can be adapted seamlessly for diverse applications. According to existing literature, such as the works of Teo et al. (2006), these nanofiber membranes excel in filtering out micron-sized particles from water, demonstrating minimal fouling.

While their potential applications are vast, nanofibers are especially significant in the preparation of materials for ultrafiltration and reverse osmosis. Electrospinning's utility is well-documented in air treatment, but its deployment in wastewater treatment remains relatively under-explored (Ramakrishna et al., 2006). A persistent challenge in membrane technology is the balance between selectivity and permeability. Given its pressure-driven nature, the method can be energy-intensive.

An electrospun nanomembrane possesses the capability to neutralize viruses or bacteria through size exclusion. However, the diminutive pore sizes of these membranes pose challenges in effectively filtering out viral agents. Such microscopic pores can hinder the flow of water. Yet, innovations continue. A notable example is a novel composite cellulose-based membrane designed to filter out bacteria while maintaining water flow, boasting an impressive 99.9999% efficacy in E. coli removal (Sato et al., 2011). This system employs positive-charged fibers to attract and capture negatively charged viruses, aligning with the stringent 2 CFU/mL criteria set by the American National Sanitation Foundation Standard.

In an interesting development, 100 nm-diameter poly(acrylonitrile-co-glycidyl methacrylate) nanofibers underwent protein functionalization, enlarging their diameter to 126 nm. These biofunctionalized nanofibers, when exposed to moisture during filtration, undergo a shape transformation. This results in a rise in pH beyond the protein's isoelectric point, revealing previously concealed functional groups and chemicals. The protein's swelling further aids in the filtration process, creating an expanded steric barrier that facilitates the trapping of nanosolids, such as metal ions.

4. Nanocomposite Membranes

Nanocomposite membranes are an innovative solution in the realm of water and wastewater treatment, bringing forth multiple benefits due to their ability to combine different materials. These membranes consist of mixed matrices or those with surface functionalization, most notably being inorganic nanofillers encapsulated within polymeric or inorganic oxide matrices (Gehrke et al., 2015).

5. Notable Benefits and Applications:

- Enhanced Hydrophilicity and Fouling Resistance: Incorporating hydrophilic metal oxide nanoparticles like Al_2O_3 and TiO_2 into membranes can boost hydrophilicity and water permeability, leading to reduced fouling. This approach also improves the membranes' mechanical and thermal stability, safeguarding against adverse impacts of compaction and heat (Maximous et al., 2010; Pendergast et al., 2011).
- Mesoporous Carbons: These are introduced as nanofillers in thin-film polymeric matrices. Post atmospheric pressure plasma treatment, these hydrophobic carbons transition into a hydrophilic state, enhancing water permeability (Wang et al., 2011).
- Biofouling Prevention: Nano-Ag and CNTs are effective against biofouling. Nano-Ag, when grafted onto polymeric membranes, restricts bacterial adhesion and biofilm formation. Meanwhile, CNTs, upon direct contact, have exhibited the potential to inactivate bacteria (Ahmed et al., 2012; Brady-Estévez et al., 2008).
- Photocatalytic Action: Photocatalytic nanoparticles embedded within membranes offer dual benefits: contaminant degradation and physical separation. For instance, TiO_2 nanoparticles have been used with metal filters for effective contaminant breakdown (Lou et al., 2012).
- Nano-ZVI for Contaminant Breakdown: Zero-valent iron (ZVI) or nanoscale metallic iron (nZVI) has shown promise in treating contaminated wastewater. Within polymeric membrane systems, nano-ZVI serves as an electron donor, boosting the degradation of contaminants (Wu et al., 2008; Qu et al., 2013).

6. Challenges and Considerations:

Despite their immense potential, scaling up nanocomposite membranes for commercial use remains challenging. Several concerns need to be addressed:

- Economic Viability: While a few nanomaterials are cost-effective, many are exorbitantly priced. Strategies for regeneration and reuse can enhance cost efficiency (Qu et al., 2013).
- Safety and Environmental Concerns: The nanoscale size poses identification and risk management issues. Thorough research is required to comprehend the potential risks of using these nanomaterials in water and wastewater treatment.
- Long-Term Efficacy: The durability and long-term performance of these technologies need rigorous testing. Only after consistent results can they be scaled up and commercialized.

In conclusion, while nanotechnology offers revolutionary solutions in water treatment, it is crucial to balance innovation with safety, efficiency, and sustainability. Only after addressing the current challenges can these technologies truly redefine the water treatment landscape.

Major Limitations Associated with Conventional Water Purification Methods

Conventional Methods	Limitations
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* From: Kunduru et al., Chapter 2017.

7. Research limitations and future related works

Nanotechnology, despite its promising applications in water and wastewater treatment, comes with an array of challenges that need meticulous attention. Here is a deeper dive into the limitations and concerns tied to this field:

7.1. High Initial Costs

Equipment and Infrastructure: Setting up a laboratory or facility for nanotechnology research involves investing in specialized equipment, which can be prohibitively expensive.

Materials: The synthesis or procurement of nanomaterials is costly, particularly for more advanced or rare materials.

7.2. Specialized Skill Set:

Nanotechnology research necessitates a profound understanding of both the macroscopic and quantum worlds. Acquiring or training personnel with the requisite knowledge can be a daunting task.

Collaborative endeavors between different disciplines, like biology, chemistry, and physics, are often essential, further compounding the complexity.

7.3. Environmental Concerns

Unpredictability: The behavior of nanoparticles in natural environments is not fully understood. Their interaction with existing ecological systems can lead to unforeseen consequences.

Bioaccumulation: There is the potential for nanoparticles to accumulate within organisms, moving up the food chain and possibly leading to toxic effects.

7.4. Human Health Concerns

Ingestion and Absorption: Nanoparticles, due to their size, can be ingested or inhaled easily, potentially causing health issues. Their ability to translocate within the body can lead them to vital organs, posing long-term health risks.

Unknown Long-term Effects: While some short-term studies exist, long-term studies on the impact of nanoparticles on human health are still in nascent stages.

7.5. Detection and Monitoring

Limitations in Current Technologies: Given the nanoscale, size of these particles, detecting and monitoring them in vast water bodies is a challenge. Advanced detection methods are still being developed.

Contamination Risks: Without effective detection systems, there is the looming risk of nanoparticles contaminating drinking water sources or aquatic ecosystems, potentially causing ecological imbalances.

7.6. Adoption and Scalability

Economic Viability: Any new technology's widespread adoption hinges on its cost-effectiveness. Currently, the high costs associated with nanotechnology limit its scalability and widespread implementation.

Public Perception and Acceptance: New technologies often face skepticism. Educating the public and policymakers about the benefits, while transparently addressing risks, is vital.

7.7. Regulatory Challenges

Nanotechnology's rapid advancement has outpaced the development of a comprehensive regulatory framework. Without clear guidelines and standards, commercializing and adopting such technologies can be mired in uncertainty.

In conclusion, while the potential of nanotechnology in revolutionizing water treatment is undeniable, it is paramount that these challenges be addressed head-on. Collaborative, interdisciplinary research, coupled with proactive policy-making and public engagement, can pave the way for safer and more efficient applications of nanotechnology in this realm.

8. Conclusion

Nanotechnology holds a transformative potential for various sectors, with water purification being at the forefront. While many nations are leaping forward, embracing this technology to address their water challenges, the Middle East, with its pressing water scarcity issues, has been slow to adopt and invest in this promising field.

Our paper has shed light on the myriad ways in which nanotechnology can revolutionize water purification processes. The technologies currently in development, as detailed in our discussion, have the potential not just to address the water challenges of the Middle East, but also to elevate the standard of living for its inhabitants. Access to affordable and clean water can significantly boost public health, social well-being, and economic growth.

Moreover, the sustainable nature of nanotechnology-based filtration can considerably reduce the environmental footprint of traditional water purification methods. This is crucial for a region that is grappling with environmental challenges, exacerbated by climate change.

However, for these solutions to transition from the realm of potential to reality, a collaborative effort is paramount. Academic institutions, industries, policymakers, and stakeholders must come together to create a cohesive strategy. Investments, both financial and intellectual, need to be channeled towards research, development, and implementation of nanotechnology in water treatment.

In sum, the Middle East, with its rich history of pioneering innovations in various fields, has an opportunity to lead once again. By embracing nanotechnology for water purification, the region cannot only address its water scarcity challenges but also position itself as a global leader in sustainable water solutions. The future is rife with possibilities, and with concerted effort, a water-secure Middle East is within reach.

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