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NANOSTRUCTURAL POLYMERS FOR WATER PURIFICATION: RESPONSE TO CLIMATE-INDUCED WATER SCARCITY BY SUSTAINABLE MATERIALS

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ABSTRACT
Due to climate change, growing population, and waste from industrial plants, there is now a worldwide water shortage. As a result, new models are being implemented to help handle the issue of water purification. Biodegradable and renewable materials can be used in Nanostructural polymers to ensure efficient and sustainable water treatment. They are capable of absorbing water efficiently and removing both kinds of waste pollutants. The review is carried out to test the effectiveness of nanostructural polymers in solving water shortage problems with respect to their chemical characteristics. The paper evaluates different issues related to using the technology, such as costs, whether the tech can be expanded, and how regulations affect its success in purifying and providing clean water. The study reveals that the technology makes the process environmentally safe and inexpensive in contrast to the previous traditional techniques.

Keywords:
Nanostructural Polymers, Water Purification, Sustainable Materials, Contaminant Removal, Heavy Metals, Antimicrobial Properties, Environmental Sustainability, Climate Change, Water Treatment Technologies, Renewable Materials.

1. INTRODUCTION

Radical changes in climate have resulted in significant environmental change that causes harm. As there are millions of people living in cities, communities are facing higher water shortages because the overpopulation in cities has increased the amount of water used each day. Through a multidisciplinary research approach, the use of nanotechnologies has enhanced the purification of available water to address the demands (Zhang et al., 2023). The field of nanostructured polymer has over 15,800 publications and over 4000 documents on methods of treating water in a sustainable manner (de Assis et al., 2021).

Based on these potentials, individuals can comprehensively assess the opportunities for the effective use of nanostructured polymers to address water scarcity in the fast-growing research area. The review covers aspects of antifouling membranes, purification of water, antimicrobial properties of polymer for photo decontamination, and development of contaminant filters. This would require converting public and government attention to directly drawing some policies and making them more aware of the detrimental effects of industrial and natural contaminants on environmental and social systems (de Oliveira et al., 2018). Consequently, systemic consequences related to water scarcity will be predicted and assessed when finding an effective solution by using advanced technological tools such as nanostructured polymers.

1.1. Background and Significance

Water purification has a long-standing history of constant technological advancements to suit prevailing social trends and global circumstances. Currently, water treatment specialists anticipate a climate change-induced exacerbation of pre-existing water scarcity (Zhang et al., 2023). Developing robust solutions to this emerging problem requires a comprehensive understanding of the interactions and entanglements between water scarcity as a multi-scalar phenomenon and the underlying purification technologies that evolve in response to such expansion of constraints (de Assis et al., 2021). In the context of supporting sustainable water purification solutions, this essay aims to articulate the relevance of studying past innovations in water purification. To this end, we review the historical development of water purification methodologies in the Western world and the insights that can be gained from such an analysis.

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Today, the importance of sustainable water purification in the interconnection between social and environmental systems is of growing interest to numerous stakeholders (de Oliveira et al., 2018). Global water scarcity is a mounting crisis that is particularly well documented. Approximately one-third of the worldwide population 2.3 billion human beings currently lives in areas facing water scarcity. By 2025, it is projected that 1.8 billion people will inhabit locations with a lack of adequate fresh water. Two-thirds of people may suffer from scarcity. Even more striking is that 4 billion people approximately two-thirds of the Earth's population encounter severe water scarcity for at least a single month every year. The natural provision of water is already impaired by ongoing pollution, which affects an estimated 1.8 billion individuals. As many as 110 million individuals worldwide live in water pollution conditions that exceed norms, driven by an increased need for water. Water scarcity primarily stems from pollution, which is forecasted to worsen as climate change sparks heightened rainfall variability that can contaminate drinking water sources. The severity and implications of this are yet to be determined. Research and interventions that mitigate the multifaceted, interconnected drivers at the root of global and local water scarcity crises are still relatively immature (Darling et al., 2017).

1.2. Objective of the Study

Nanostructural polymers, made from sustainable materials, have been developed using a one-step eco-friendly process that is also water-based (Zhang et al., 2023). So far, these nanostructural polymers have shown great potential for water purification as adsorbents and flocculants (de Assis et al., 2021). As climate change is causing water to become scarcer and more expensive globally, the challenge to the research community is to innovate new water purification technologies that are as sustainable as clean water itself (de Oliveira et al., 2018). The objective of this paper is to explore the use of these nanostructural polymers in the development of a novel photoactive membrane for water purification with potential applications in decentralised water treatment systems. A detailed investigation into the fate of these nanostructured polymers within the polyethersulfone membrane was also conducted. This investigation aimed to answer two key research questions: Can nanostructural polymers made from renewable biological materials be further used in the design of unique multifunctional membranes for water purification by utilising their sorption properties, and does blending of membrane components differently impact photocatalytic activities and excellent removal capabilities in a membrane? Part of improving water quality involves eliminating materials like metal ions, microbiomes, organic matter and all other contaminants found in water sources. It is important to purify water to deal with water scarcity in a way that safeguards the environment. Antimicrobial surfaces and adsorbents that rely on nanotechnology are among the materials used in this process (Darling et al., 2017). The findings from the research can help in the development of advanced models for purifying water that support different SDGs (Pires da Mata Costa et al., 2021).

2. FUNDAMENTALS OF WATER PURIFICATION

Previously, methods such as reverse osmosis, oxidation, electrolysis, and UV treatment were utilised for purifying water (Zhang et al., 2023). The process of oxidation ensures bacterial nourishment; sedimentation creates differences between liquid and solid structures. In contrast, UV treatment ensures the disinfection of liquids through the transfer of radiation energy to the cells or DNA of pathogens. As far as reverse osmosis is concerned, the movement of water from a higher-pressure area to a lower-pressure area through a semi-permeable membrane to remove salt and other organic matter is regarded as reverse osmosis (de Assis et al., 2021). Electrolysis oxidation is used to obtain clean water by removing various dissolved gases from raw water. However, it has some limitations as well. Water vapour and condensed water strains are released after boiling during distillation (de Oliveira et al., 2018).

With the advancement in human development, the emergence of diversified and intricate chemicals from commercial, domestic, industrial, agricultural, and other operations contributed to water pollution, increasing environmental deterioration. Although most of the current water purification techniques are beneficial in the public eye, the complexity of the types of pollutants led scientists and commercial communities to develop modern, simple, chemical-free, and low-cost methods and substances to address the diversity and enormity of the contamination caused (Darling et al., 2017). Researchers have laid down some principles of environmental science that purify water, such as sedimentation, coagulation, precipitation, oxidation, ion exchange, activated carbon absorption, and membrane processes. Nanostructured materials with a diameter of about 1-100 nm were gradually found to be advantageous in improving the existing list of purification techniques (Pires da Mata Costa et al., 2021). Such findings point to the need for a change in treatment and removal principles to coincide with current knowledge, such as the global water crisis caused by climate change (Zhang et al., 2023).

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2.1. Traditional Methods

Human beings are the only species that distil and clean water by breaking the natural water cycle into small compartments. Over the years, different processes and techniques have been developed to purify impure water. A conventional technique of water purification is to let suspended dirt and debris settle to the bottom of the water, for which large-scale gravitational settling equipment is used (Zhang et al., 2023). Following the gravitational process, large-scale beds or filters are used over a long time to allow the removal of bacteria and germs from the water. Then, the addition of chemicals, particularly chlorine, is followed, which is meant to kill the parasites and microscopic invaders that parasitise the human body, damaging the kidneys, skin, and throat and making water potable (de Assis et al., 2021). This conventional process has been increasingly modified by optimising several new techniques (de Oliveira et al., 2018).

Although the role of the traditional water treatment system in water purification is envisaged as essential, it possesses several ironies as it requires periodic interruption of water supply to backwash the multi-stage sand bed filter in some removal strategies for iron, defluoridation, or adaptation to other chemical contaminants, a turbid layer is designed to appear over the conventional filter. The outer layer, however, has to be either removed or replaced from the filter, which is an academic challenge. Besides requiring carcinogenic chlorine, a considerable amount of chemicals used in the coagulation process, particularly aluminium, makes the treated water considered potential chemically hazardous waste, leading to the use of virgin chemicals (Darling et al., 2017). The coagulated turbidity is not cost-competitive in the affordable water purification system for society (Pires da Mata Costa et al., 2021). Even basic fuels are transported. Therefore, sustainability was aimed.

3. NANOSTRUCTURAL POLYMERS

Nanostructural polymers are organic macromolecules in the macro-gigadalton range that form self-organised, non-covalent, permanent co- or supramolecular structures (Zhang et al., 2023). Nanostructuring is induced by advanced organic chemistry, and the macroscopic shapeability of nanoscale-structured polymers is introduced by directional bonding, yielding mechanical, covalent, or reversible topological intermolecular nets or frameworks (de Assis et al., 2021). These robust nanostructured materials possess hierarchical, porous, or fibrillar architecture with nanocavities or nanochannels. Industrially used polymers known as nanostructured include polyolefins, sol-gel glasses and aerogels, three-dimensional micro- and nano cross-linked polymers, and thermoplastic or metalloplastic networks (de Oliveira et al., 2018).

Nano structural polymers have been employed for various purposes in the rapidly growing field of polymer nanotechnologies, such as drug and cell culture dosage, biological imaging, marking, nanomedicine, adhesives, coatings, paints, biomaterials, and tissue or bone mimics, in holography or liquid crystal displays, micro membranes and sensors, packaging, and encryption. Their properties make them potentially useful in applications where large-scale filtration and removal of pollution from water are required. The scope of the world's recent press releases and patents that claim synthetic procedures of various types of polymeric hydrogels demonstrates the growing interest in many applications for these novel superabsorbents in connection with water treatment and water/wastewater purification processes, as well as in agricultural applications, and relation to polymer electrolyte membrane fuel cells or as actuators, sensors, or scarifying transdermal components for medical purposes (Darling et al., 2017).

Therefore, new organisations of advanced nanomaterials and devices are still the focus of modern solid-state science, not the least in view of the ecological aspects of life and the impact of solid-state technology on future planet Earth (Pires da Mata Costa et al., 2021). In the following work, we tried to approach the above aspects of nanostructural polymers and their link to water in an approachable way, such that it may serve as introductory material for researchers active in other fields of science to explore the significant potential that efficient removal of organic and inorganic objects from water may express in the context of the ever-increasing climate-induced water scarcity (Zhang et al., 2023).

Nanomaterials	Adsorption Capacity	Biodegradability	Cost	Toxicity
P13	High	Biodegradable	Low	Non-toxic
Magnetarella	Medium	Biodegradable	Medium	Non-toxic
SCMs	High	Biodegradable	Medium	Non-toxic
Dehalogenase	Low	Biodegradable	Low	Non-toxic
CNT	High	Non-biodegradable	High	Toxic

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Class II Hydrophobins	Medium	Biodegradable	Medium	Non-toxic
Elastin-like Proteins	High	Biodegradable	Medium	Non-toxic

Table 1: Properties of Nanostructural Polymers Used in Water Purification

3.1. Definition and Characteristics

'Nanostructural polymers' are here taken to refer to a bulk material based on polymer building blocks, where the characteristic length on a lower scale is smaller than or in the order of 100 nm (Zhang et al., 2023). These functional units interact directly or are tethered to the same bond network as the polymer building blocks. As these are prepared via step- or chain-growth polymerisation or are post-modifications to linear chains, they might need to be rather reactive to compete with the reaction rates (de Assis et al., 2021). Between nanostructural polymers, different and often unique combinations of the following can be obtained systematically: build-up of size-controlled primary structure, the ability to change functionality via non-radical steps in a contradicting environment of radical termination, thermal rearrangement capacity, networking ability, and chemical stability.

3.2 Key characteristics and advantages

Materials in which the characteristic length is close to the molecular size have different bonding topologies. Similar proportions on macromolecular size scales could lead to different material properties, making the "nanostructural" elements attractive for a variety of applications, just as low-dimensional metals or zeolites are compared to bulk metals or regular crystals (de Oliveira et al., 2018). The reactive "end groups" that are implied in the definition mean that the nanomaterials approach the equivalent surface-to-volume ratio of an emulsion or a foam, which is central in all purification processes that are based on material or interfacing as one essential component. Furthermore, the polymer structures exhibit mechanical and chemical properties chosen in advance, in some cases even conjugated functionalities, which make the system even more versatile. In summary, nanostructured polymers could be compared to an emulsion/foam but with properties designed in advance (Darling et al., 2017).

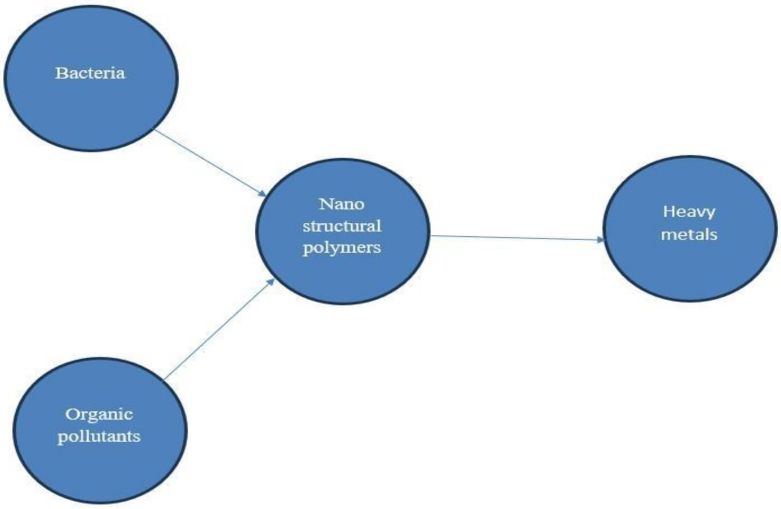

Figure 1: Diagram of Nanostructural Polymers in Water Purification

4. CLIMATE-INDUCED WATER SCARCITY

Global climate change is expected to increase the vulnerability of the population, especially in already drought-prone regions (Zhang et al., 2023). The reduction of water resources correlates with an increase in CO2 concentration. Changes in climate trigger severe weather and extreme events, inter alia, through precipitation reduction, changes in rainfall and runoff patterns, and the increase in evaporation (de Assis et al., 2021). Drier regions will become even drier, while wet areas will become wetter. The available amount of water per person on Earth is almost 83% less than it was 50 years ago. Available potable water percentages are even lower, standing at 29.2% of the available water 50 years ago. The main causes of water scarcity today include an ever-increasing

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demand for water-fueled by a rising local and global population and inefficient, non-sustainable, and irresponsible management practices (de Oliveira et al., 2018). Globally, water scarcity is anticipated to intensify because of socioeconomic and climate change-related interventions (Darling et al., 2017). In order to prevent this situation from further intensifying, innovative water management strategies need to be developed and implemented. Efforts to increase the area used for agriculture, as well as more extensive use of bioenergy, are also generating worsening environmental conditions through acidification, the spread of eutrophication, and lower levels of fresh water (Pires da Mata Costa et al., 2021).

4.1. Causes and Impacts

The ever-increasing global population, accompanied by industrial activities, rapid urbanisation, mainly in the developing world, and the introduction of innovative, refined lifestyles dependent on technology, means higher per capita demand for water, as well as the use of more capital and water-intensive agricultural practices, has decreased the amount of flowing, clean water and reshaped the vast natural reserves of water (Zhang et al., 2023). The majority of the Earth's available water supply is generally geographically inaccessible, physically diffuse, temporally erratic, or economically impractical to collect and manage (de Assis et al., 2021). The climatic impact on global water systems has increased the frequency of dry periods, particularly in the form of longer dry seasons and incidents of lower annual precipitation (de Oliveira et al., 2018). Evaporation is an intensified consequence as temperatures increase. A warmer atmosphere can accommodate more water vapour. Such extensive changes in the moisture-holding capacity and the burst of summer heat waves drive the demand for water for agriculture and human welfare. The affected developing and impoverished regions are excessively vulnerable to these compound events.

Each of these events has many long- and short-term implications that affect ecosystems and humanity. This is evident in the frequent incidents of unclean and unsustainable sources of drinking water, which increase the demand for energy, money, and resources for water purification and decontamination (Darling et al., 2017). Water scarcity poses serious consequences on overall human health, natural ecosystems, lifestyle, and social well-being. Nearly 842,000 people worldwide die a year from substandard water and inadequate water, sanitation, and hygiene; poor sanitation leads to poor hygiene and undernourishment, further exacerbating the chances for infectious diseases (Pires da Mata Costa et al., 2021). With an already dwindling supply of fresh water, considering that future global hydrated energy requirements for the human population alone are projected to increase by more than 55% over the next two decades, water insecurity governance is urgently required, and integrated mitigation and adaptation plans will be crucial in decision-making by policymakers concerning water and energy policies (Zhang et al., 2023).

Young children are among the most at risk of exposure to dirty water, waterborne diseases, skin sicknesses, and other water-related threats and hazards. Over 73 million working days are lost due to water-related diseases caused by inadequate access to industry and crop water, conservatively estimating a loss of $160 billion to complete global economic productivity (de Assis et al., 2021). The immediate cause of reduced, accessible, available water per capita in these affected areas is not so much physical scarcity as it is intensive and inefficient use, mismanagement of available water resources, such as ecosystems, and environmentally unsustainable channels of use (Darling et al., 2017). These detrimental practices, particularly relevant to agriculture and health, are the primary causal agents of the multidimensional water scarcity crisis. The agricultural industry requires water to promote and sustain hundreds of thousands of agricultural, perennial, and rain-fed food crops, plants, and trees. While regions in the northern hemisphere and many sub-Saharan and East African countries have seen increased average volumes of rainfall, uneven rainfall patterns produce irregular rain for the staple cereal crops, such as millet and sorghum, with more frequent dry periods and heavier wet seasons.

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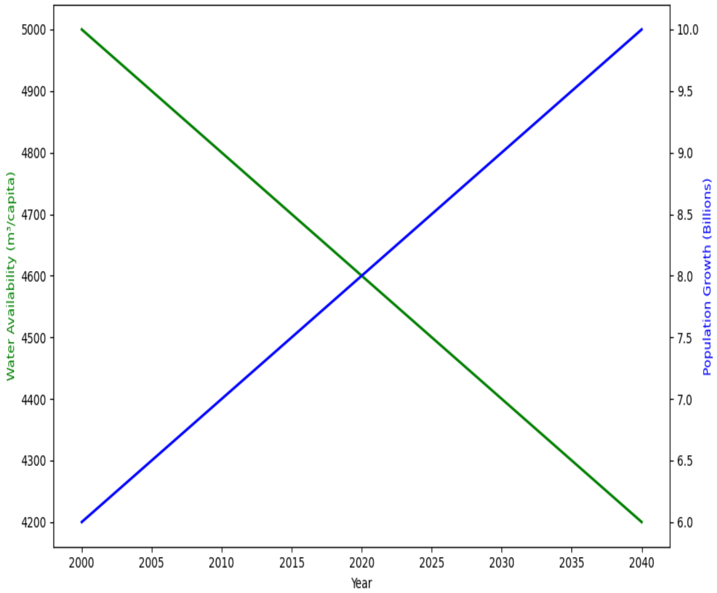

Figure 2: Impact of Climate Change on Water Availability

Region	Current Water Scarcity (%)	Projected Future Scarcity (%)
Africa	30	45
Asia	25	40
Europe	10	20
North America	8	12
Latin America	20	30

Table 2: Global Water Scarcity by Region and Projected Future Impact

5. SUSTAINABLE MATERIALS FOR WATER PURIFICATION

Rapid climate change has accelerated water scarcity to the extreme globally (Zhang et al., 2023). Over hundreds of years, conventional materials and chemicals, particularly carbon-based ones, in purification systems have caused severe environmental impacts. Therefore, eco-friendly and sustainable materials are now needed for water purification as alternatives to current technologies (de Assis et al., 2021). These emerging materials for next-generation separation technology can address various applications in filtration and ensure convenient separation operations (de Oliveira et al., 2018). Sustainable materials, such as biopolymers, natural polymers, and polymers processed from renewable resources, possess some favourable properties, such as low-cost preparation, abundant resources, biodegradability, bioavailability, recyclability, environmental friendliness, nontoxicity, and biocompatibility, among others. They have applications in various technologies to provide huge accumulations of highly efficient and cost-effective raw materials for physical and chemical modifications, enhancements, or rebuilds of their surface structures or microbial attachments for water purification (Darling et al., 2017).

Large numbers of novel adsorbents have been introduced into purification methods to reduce the biological cost of applying chemicals and to mitigate both fundamental and system-based contaminations (Pires da Mata Costa et al., 2021). Advanced materials can enhance the self-cleaning ability of membranes via photoacoustics and interfacial photocatalysis to mitigate front-end colloidal aggregations, control bacteria attachment and biofilm formations, attenuate membrane surface propensities, inhibit rancidity and colouration of concentrated nutrients, reduce environmental and ecosystem impacts from membrane surface bio-grafting bacteria, and enhance chlorine degradation and degradation-based fumigations (Zhang et al., 2023).

5.1. Importance and Types

In the future, as our water quality becomes even worse because of climate change, we need to find new materials with positive properties and working processes that are sustainable and can be scaled to industrial dimensions in water purification (Zhang et al., 2023). These materials and processes respond to climate-induced water scarcity

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(de Assis et al., 2021). Many materials studied have a large environmental and health-related impact; many of them consist of inorganic materials or organic materials based on fossil feedstock. All of them will remain in the environment and will neither degrade nor be reused (de Oliveira et al., 2018). Many countries are working on finding alternatives for these materials. Several of these materials for water purification and resource recovery have been reviewed.

Materials that can be sustainably used in water purification and resource recovery are typically natural materials, like biomass or clay. However, they can also be manufactured using renewable feedstock and following processes that do not have a zero impact on the environment (Darling et al., 2017). However, they are biodegradable, like most polymers, or robust and can be reused after a specific period, like activated carbon. Each of them has typical advantages and disadvantages in their use in environmental technologies and can be used in a complementary way due to their different interaction mechanisms with contaminants (Pires da Mata Costa et al., 2021). The family of natural, renewable, and biodegradable materials can also be included in different families based on different criteria: they can also be low-cost and normally available at the test site or otherwise cause low mobility costs (Zhang et al., 2023). Some case studies of the application of these materials in the water sector are provided here.

The European Union has already allocated several billion euros to become a world leader in water-related technologies that enable the transition to sustainable management of water resources in order to integrate circularity and synergies between water, food production, and governance, especially in developing countries with water scarcity (de Assis et al., 2021).

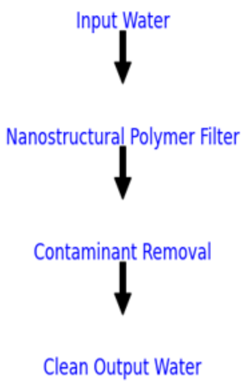

Figure 3: Water Purification System Using Nanostructural Polymers

6. INTEGRATION OF NANOSTRUCTURAL POLYMERS AND SUSTAINABLE MATERIALS

Nanostructural polymers for advanced water purification, when integrated with sustainable materials, have the potential to synergistically address emerging opportunities in mitigating the effects of climate-induced water scarcity (Zhang et al., 2023). These new materials could also be effectively utilised for next-generation water technologies, combining the ultra-efficient purification of water using less energy with minimised environmental and health impacts (de Assis et al., 2021). Up to now, several approaches have been investigated to broadly cover potential features and opportunities: (1) nanostructural polymers as biofilm inhibitors and, therefore, desirable non-toxic potable water membrane filtration technology; (2) synthesis of hierarchical composites through the integration of nanostructured polymers and eco-friendly filtration materials and reusing them in a desalination system; and (3) environmental water treatment applications using nanostructured membranes (de Oliveira et al., 2018). The main drivers towards greener water technologies and these three approaches are interesting outside the area of polymer nanomaterials. It is also interesting to see that incorporating new functional materials found in the composite and novel membrane technology fields has allowed researchers to work in an area of higher application and real-world impact because of complementary expertise.

Recently, these proposed visions have been realised, demonstrating such complementary features. For example, muscone-infused polybenzimidazole membrane, a hydrocarbon-based polymer, showed enhanced resistance to biofouling without the incorporation of any chemical compounds, and it could be a promising potable water treatment system (Darling et al., 2017). The integration of nanostructured polymers and eco-designed, sustainable filtration materials has opened a new path because it can lead towards sustainable technology development, recycling of eco-friendly materials, and energy recovery (Pires da Mata Costa et al., 2021). Self-propelling hierarchical ATP-based dual gate-axis smart nanocarriers loaded with antibiotics that were embedded in

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amphiphilic sustainable ball-shaped nanostructures to prepare an intelligent nanostructured polymer. The potential and possibilities of incorporating recent advances in nanostructured polymers into sustainable technological platforms to initiate a flexible framework for more efficient water treatment (Zhang et al., 2023). In order to overcome current fundamental and practical challenges facing commercialisation, including scalability and accessibility, further research is required for interdisciplinary scientists working on new technologies (de Assis et al., 2021).

Technology	Energy Use (kWh/m3)	Cost ($/m3)	Efficiency (%)	Environmental Impact
Reverse Osmosis	3	1.5	95	High
UV Treatment	0.5	0.8	90	Medium
Nanostructural Polymers	0.2	0.6	85	Low

Table 3: Comparison of Traditional and Nanostructural Polymer-Based Water Treatment Technologies

7. APPLICATIONS OF NANOSTRUCTURAL POLYMERS IN WATER PURIFICATION

Nanostructural polymers have shown their potential in water purification systems on the laboratory scale, pilot scale, as well as field scale and community scale, providing various scales of water purification solutions (Zhang et al., 2023). Water purification using nanostructural polymers, including P13, magnetarella, SCMs, dehalogenase, pH-sensitive materials, CNT, class II hydrophobins, and engineered elastin-like proteins, has been demonstrated for the removal of emerging pollutants (de Assis et al., 2021). Utilising such materials for enhanced membrane technology began to be tested in the 1990s and was based on inorganic hollow fibre supports. These supports are largely inert towards the processes occurring within their inner pores. However, they have the disadvantage of high cost, limited mechanical flexibility, and low further interventions on the membrane material (de Oliveira et al., 2018). These disadvantages can be resolved by the use of hydrophilic reverse phase polymer-coated and pHEMA as ultrathin film coatings on hydrophobic hollow fibres or flat sheets.

The utilisation of nanostructural polymers has been tested in the removal of various types of water pollutants, such as heavy metals, radionuclides, inorganic solutes, VOCs, fungi, spores, bacteria, cysts, viruses, organics, and emerging pollutants for drinking water purification in different contexts such as surface water, wastewater, brackish groundwater, municipal water, raw water, treated water, etc., by using pressure-driven, vacuum-driven, gravity-driven, integrated membrane, and biofilm technologies (Darling et al., 2017). The documentary evidence clearly points to the potential of nanostructural polymers to provide novel water purification solutions (Pires da Mata Costa et al., 2021). The validity of these research studies is not small or applicable only to particular research areas or the geography and socioeconomic status these studies cover. It is not the effort of a single research group but multiple universities, organisations, funded projects, patents, etc. The involvement of multiple authors from around the world confirms the generalised applicability and potential of these nanostructural polymers (Zhang et al., 2023).

Nanomaterials	Heavy Metals	Radionuclides	Bacteria	Viruses	Organics
P13	85	80	90	70	75
Magnetarella	78	65	85	60	70
SCMs	80	72	85	68	73
Dehalogenase	70	60	75	50	65
CNT	88	80	90	75	78
Class II Hydrophobins	83	77	89	72	74
Elastin-like Proteins	86	82	92	78	80

Table 4: Water Contaminants Removed by Nanostructural Polymers

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7.1. Drinking Water Treatment

The application of nanostructural polymers for drinking water treatment has received much attention, which is not surprising considering the importance of water safety and the rigorous national and international standards that drinking water must meet (Zhang et al., 2023). Drinking water treatment plants are responsible not only for removing possible contaminants but also for maintaining water filters and supply systems that minimise the possibility of secondary contamination caused mainly by biofilm formation on pipe walls (de Assis et al., 2021). An overview of drinking water production and the possible points of intervention that make use of nanostructured materials to improve the quality of drinking water further has already been provided (de Oliveira et al., 2018). This review will present state-of-the-art solutions in low-cost drinking water treatment that provide better protection for people from bacteria, viruses, and cysts. Although the introduction of highly effective solutions containing silver into nanomaterials is becoming increasingly important, the most innovative principle of introducing nanostructural polymers into drinking water treatment is the possibility of extending the range of substances retained by filtration in order to obtain the highest quality water.

Significant increases in the contaminant adsorption capacity of membrane bioreactors and slow sand filters containing nanostructural polymers have been reported (Darling et al., 2017). Parallel to these studies were in-depth chemical and structural analyses that helped us understand the mechanism of action of these innovative filters. The performance and real operating possibilities of such state-of-the-art solutions for slow sand filtration technology were demonstrated using multi-barrier treatment (Pires da Mata Costa et al., 2021). The results show the potential for improvement in virus and microbiological recovery, further reductions in total organic carbon and endotoxin levels in drinking water, and limits for trihalomethane production, even below the levels set by legal limits (Zhang et al., 2023). At the same time, the scalability of such state-of-the-art filtration processes for large plants was confirmed. The introduction of an innovative filtration system into a large municipal water treatment plant is described with an analysis of the total cost of the investment and operating costs (de Assis et al., 2021).

7.2. Industrial Water Treatment

7.2.1. Industry Application

The application of nanostructural polymers to the treatment of process water in industry represents the design of materials towards particular needs (Zhang et al., 2023). The materials are designed to provide a final stage of treatment where multiple stages exist, and complete removal of water-based impurities is required (de Assis et al., 2021). Applications thus frequently address sectors such as mining, where water is used in a variety of ways, including mine dewatering, ore washing, or as part of associated smelting and refining. Often, these requirements are thousands of kilometres from available fresh water and are undertaken in resource-constrained environments (de Oliveira et al., 2018). Other relevant sectors include power generation and transmission, which could use saline or brackish cooling water, and arrangements that reflect common refinery practices for industrial water treatment. Effective performance may also require that the technology is safe and cost-effective (Darling et al., 2017). Waste treatments are also a part of these processes, including the cleanup of escapes from production processes and dust. Many of the materials emerging in these industrial water treatment sectors offer enhanced methods to remove heavy metals and radionuclides, depending on the process contaminants (Pires da Mata Costa et al., 2021).

7.2.2. Introduction

Natural water can be contaminated with impurities such as sediment, disease vectors, and chemicals. Industrial waters experience the same, with some impurities likely to be added during both production and through atmospheric deposition (Zhang et al., 2023). Impurity lists can reflect the variety of processes undertaken by an industry. These may include specific ores, minerals, or reagents. Depending on the process, impurities can include heavy metals, sulfates, nitrates, and arsenates (de Assis et al., 2021). The industry also deals with impurities removed from entities like coastlines and gas fields. Industrial treatment waters regularly have large amounts of waste, and new water is often produced post-mining or post-use of the water for something else. Restored waters are often discharged into nearby natural water bodies and may require re-oxygenation and removal of solids (de Oliveira et al., 2018). As the demand for freshwater increases globally and climatic events such as flooding or drought become more extreme, training lakes of very large cleanings become ultimately impossible, wasteful, and unsustainable. For sensitive receptors, no significant waste can leave the mining zone. Thus, mining water treatments tend to offer percentile or percentage removals that the operator or regulator will impose as limits (Darling et al., 2017). This industry is significant throughout Australia. There are significant improvements in performance for these final treatment waters that are essentially additional waste streams with very low size

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specifications. Regularly, both the footprint size and capital costs are substantially reduced, sometimes by as much as 90% (Pires da Mata Costa et al., 2021). In mining, waste treatments grow in response to the quantity of larger-size particles required to be removed to allow disposal onto a solid substrate. Piling, bundling, or even stacking requires a myriad of sizes and low-fine waste. Fine waste can be separately disposed of via in situ water treatment cells. All of this ultimately reflects the need for waste to be capable of settling without requiring a large footprint (Zhang et al., 2023).

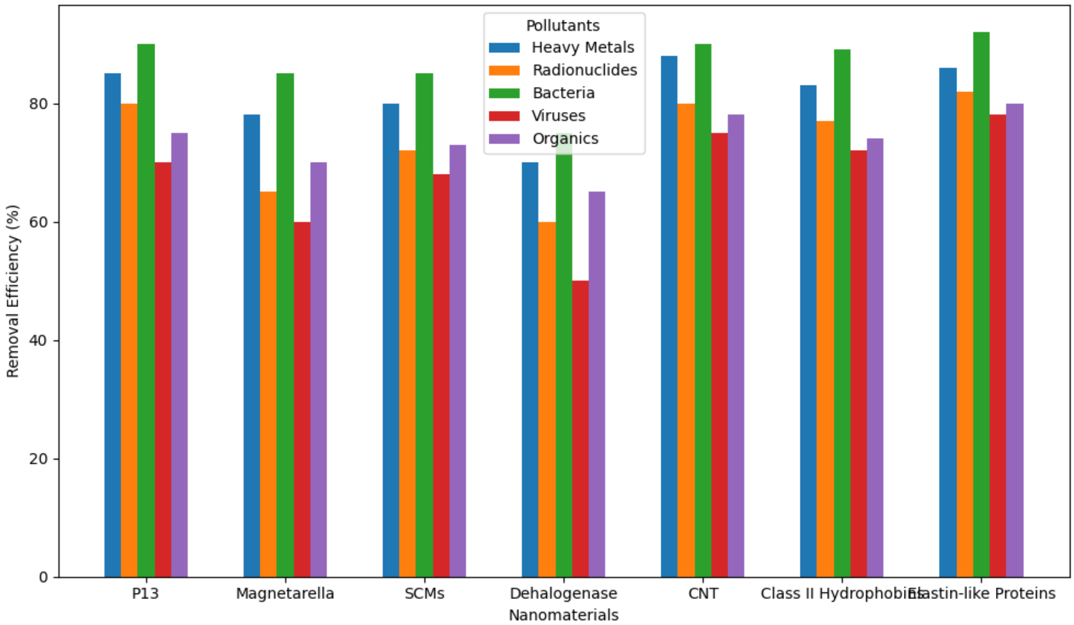

Figure 4: Nanostructural Polymers in Water Purification

8. CHALLENGES AND FUTURE DIRECTIONS

Although significant efforts are made in the field of water treatment for applying nanostructural polymers, this antibody technology has not been fully deployed (Zhang et al., 2023). In this section, we highlight some important issues in the hope of stimulating future discussions and research. The fundamental question is how 3D nanostructure-based treatment can be best optimised to function and scale (de Assis et al., 2021). The optimal technology has to be adaptable to local environmental conditions, to the water to be treated, to operational equipment and know-how, as well as to finances and political decision processes if they spur from the developed world or are appropriate in already sophisticated water treatment systems (de Oliveira et al., 2018). There are several practical problems in the operational deployment of unconventional treatment technologies. The most economical low-energy solutions tend to be low power; the use of powerful radiation, such as ultraviolet, poses the risk of creating decomposed, degenerated toxic byproducts. Moreover, the materials and particularly their precursors are high in cost for extensive research in order to investigate long-term stability and influence, as well as harmful byproducts on health and the ecosystem (Darling et al., 2017).

Of particular interest will be to assess whether there are any potential consequences for the ecological environment due to the disposal of imperfections from the conversion of barrier membranes, heavy industrial synthesis and processing, and landfill of unused mesh (Pires da Mata Costa et al., 2021). The nontoxicity and safety considerations of the new polymer systems will represent a further research concern of significance in the near future (Zhang et al., 2023). It will thus be crucial to design an enabling, environmentally benign, simple, rapid, and cost-effective regulatory framework in order to inspire and guide innovation through a regulatory-based approval process (de Assis et al., 2021). Where necessary, administrations, especially those working in developing and low- and middle-income countries, need to be more informed in order to support dialogue and a priori discussion through policy, regulatory, and reimbursement pathways. Demonstrations are essential near-term outcomes and blueprints for all potential manufacturers, creators, inventors, policymakers, and civil society (Darling et al., 2017).

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Therefore, coordinated efforts are required by regulatory agencies, farmers, researchers, and entrepreneurs because collaboration is greatly welcomed in the end. According to the technology-needs assessment, it is proposed that the development of environmental protection freshwater membranes should focus on at least two dimensions: first, the research should focus on the long term towards decreasing energy and water use and minimising the use of debilitating goods (Pires da Mata Costa et al., 2021). If the developed data suggests the need to move from one integrated system to another, the risk of emplacement arises. It is theoretically and economically conceivable that through a combination of new advances and sustained technological growth, the hazard of premature salinisation can be mitigated and transformed (Zhang et al., 2023). Second, the usability and disposal of the materials are particularly relevant when considering developing countries and emerging high-growth economies where many of the industrial processing liabilities are directly linked with malfunctions in the water sector in addition to a range of unsustainable practices (de Assis et al., 2021). Multidisciplinary work beyond and among current research silos, such as a combination of agrarian engineers, environmental lawyers, chemists, biologists, materials scientists, physicists, and others, could prove novel and path-breaking in market terms. The new approach to systems thinking is likely capable of developing a common that respects multicultural diversity, ecosystems, and development beyond market fundamentalism (Darling et al., 2017).

8.1. Technological Challenges

Advancements in commercially viable solutions for water purification are challenged by some crucial technological problems (Zhang et al., 2023). Firstly, the long optimisation and characterisation steps, as well as low production yield may be problematic during scale-up (de Assis et al., 2021). A need for comprehension and optimisation arises in synthetic procedures to engineer the composition of molecular aspects of nanostructured polymers as outlined by Oliveira et al. (2018). The interdisciplinary research groups focus on developing processing conditions, bioinspired functional polymers, and scalable synthesis between the function and structure of polymers (Darling et al., 2017).

Furthermore, researchers have developed strategies for validation that enhance the technological viability of the materials developed. This is done by integration of emerging and existing paradigms that are relevant to treatment of water (Pires da Mata Costa et al., 2021). New research on the materials needs to inspire valuable discussions and collaboration among policy makers and researchers. Scientific advancements will only be maximised and create meaningful change to address the technological challenges and opportunities identified by partnerships across all sectors (Zhang et al., 2023). Finally, emerging nanostructured polymers can drastically reduce water treatment costs and environmental burdens when technological challenges are overcome, and these polymers are used commercially, given their inherent sustainability as biodegradable materials (de Assis et al., 2021).

8.2. Environmental Considerations

The introduction of any new material into the environment and the new environmental applications must certainly take into account the possibility of additional burdens on ecosystems and the environment due to the use of resources, energy, or the application of additional or supplementary raw materials (Zhang et al., 2023). Adverse side effects of new materials on natural surroundings cause a variety of concerns. This is why the ENMs portend considerable promise for a multitude of applications, not forgetting about the cautious assessment of appropriate proportions for safety issues (de Assis et al., 2021). In summary, the inherent characteristics of new materials depend not only on their functionality but also on their potential environmental impact (de Oliveira et al., 2018).

Nanostructural polymers aimed at water purification generate numerous ecological considerations that constrain their use in sustainable and environmentally sound approaches, potentially leading to an appropriate version of the European Green Deal. Polymers are produced and input to the environment in high amounts, and if they are not inherently safe, they could lead to adverse impacts (Darling et al., 2017). As a result, end-of-life practices and their associated ecological consequences should be conceived at the outset. Important parameters to take into account include the release of free monomers, biodegradability, and accumulation, including the potential for chronic effects (Pires da Mata Costa et al., 2021). The environmental release of any nanostructured polymers and degradation products thereof bears the imposition of prior production of a risk assessment (Zhang et al., 2023). The control of the nanostructural polymer formulation and charges thereof may influence the toxicity characteristics. The impact of life cycles, both for our activities and for the synthesis or the full building of these products, has not been studied in depth (de Assis et al., 2021). Consequently, the use of nanostructured materials can generate secondary problems and relevant management. Additionally, their incorporation into the food chain might even become a long-term burden or even toxic for fresh waters and the main oceans.

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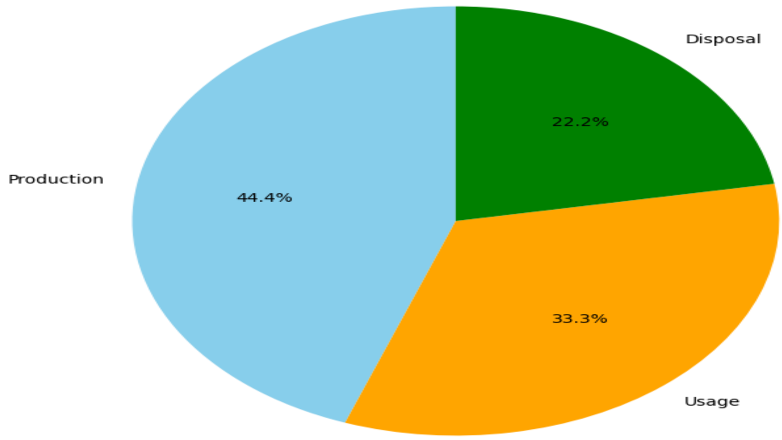

Figure 5: Lifecycle Assessment of Nanostructural Polymers in Water Treatment

9. CONCLUSION AND RECOMMENDATIONS

The paper discusses the uses of specially built polymers in water purification and notes their possible impact on alleviating water scarcity caused by climate change. The work indicates that nanostructural polymers work in treating water because they eliminate contaminants, help the environment, and function due to their chemical characteristics (Zhang et al., 2023). Water purification models have shown that such materials are significant in laboratory and practical adjustments because they manage to eliminate various contaminants such as microorganisms and different pollutants. The examples provided evidence that this technology, based on material polymers, can be scaled up and used in everyday situations (de Oliveira et al., 2018). The need to introduce technology for policy support and lack of innovation arises because it has been hard to cope with scalability, costs and regulations (Pires da Mata Costa et al., 2021).

Recommendations

- Nanostructures can be used in water treatment methods, and efforts should be made to find affordable models.
- Introducing regulations and support for safely and efficiently using polymers to clean water.
- Teaming up with relevant groups such as governments, leading organisations and various industries to tackle obstacles related to scale, expenses and frameworks.

Further investigations by scholars need to find ways to reduce expenses, expand the technology and ensure suitable regulations for these systems in water purification.

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