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REVIEW

Innovative Approaches in Water Decontamination: A Critical Analysis of Biomaterials, Nanocomposites, and Stimuli-Responsive Polymers for Effective Solutions

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ABSTRACT

In recent years, smart materials have emerged as a groundbreaking innovation in the field of water filtration, offering sustainable, efficient, and environmentally friendly solutions to address the growing global water crisis. This review explores the latest advancements in the application of smart materials—including biomaterials, nanocomposites, and stimuli-responsive polymers—specifically for water treatment. It examines their effectiveness in detecting and removing various types of pollutants, including organic contaminants, heavy metals, and microbial infections, while adapting to dynamic environmental conditions such as fluctuations in temperature, pH, and pressure. The review highlights the

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remarkable versatility of these materials, emphasizing their multifunctionality, which allows them to address a wide range of water quality issues with high efficiency and low environmental impact. Moreover, it explores the potential of smart materials to overcome significant challenges in water purification, such as the need for real-time pollutant detection and targeted removal processes. The research also discusses the scalability and future development of these materials, considering their cost-effectiveness and potential for large-scale application. By aligning with the principles of sustainable development, smart materials represent a promising direction for ensuring global water security, offering both innovative solutions for current water pollution issues and long-term benefits for the environment and public health.

Keywords: Smart Materials; Water Purification; Nanocomposites; Stimuli-Responsive Polymers; Sustainable Water Treatment

1. Introduction

The world's growing population, urbanisation, industrialisation, and demand for clean water have all combined to put tremendous strain on the world's water supplies. Heavy metals, organic pollutants, pathogens, and other hazardous materials have contaminated freshwater supplies as a result of pollution from industrial waste, untreated sewage, and agricultural runoff[1]. To address these problems, traditional water treatment techniques like filtration, chemical coagulation, and activated carbon adsorption have been widely used. However, these methods frequently have drawbacks in terms of effectiveness, expense, energy usage, and the incapacity to target a variety of contaminants in a targeted manner. This has made it necessary to investigate new, more flexible water purifying systems[2].

Smart materials have become a game-changing water treatment technology in recent years. These materials, which are sometimes referred to as intelligent or responsive materials, have the extraordinary capacity to alter their chemical or physical characteristics in reaction to outside stimuli like light, pH, temperature, or electrical fields. Materials with high specificity and efficiency that can actively detect, trap, and remove pollutants from water systems can be developed thanks to their dynamic behaviour[3]. There are many different kinds of smart materials, such as bio-derived materials, stimuli-responsive polymers, and nanocomposites, each with unique benefits when it comes to removing pollutants from the environment. It is conceivable to create water treatment solutions that are not only more effective but also more energy-efficient and environmentally beneficial by taking advantage of the adaptive nature of smart materials[4].

Although smart materials hold great promise for water treatment, there are still several obstacles in the way of their practical implementation. Before these materials are used in practical situations, concerns including long-term stability, cost-effectiveness, and scalability need to be resolved[5]. To guarantee sustainability, the environmental effects of creating and discarding smart materials—especially those involving nanomaterials—must also be carefully considered. This review offers a thorough analysis of the most recent developments in smart materials for water purification, assessing their modes of operation, particular uses, and the difficulties in implementing these technologies on a large scale. We hope to shed light on the challenges and advancements in this area and offer suggestions for future paths for smart water treatment technology research and development[6].

2. Materials and Methods

2.1. Literature Selection and Curation Methodology

A methodical strategy was used to choose and curate pertinent literature in order to guarantee a thorough and up-to-date review of smart materials in water treatment. Keywords like "smart materials", "water purification", "biosorption", "nanomaterials", "responsive polymers", and "environmentally friendly filtration" were among the search terms used. Major databases such as Scopus, Web of Science, and Google Scholar were searched, with an emphasis on articles from the last decade to ensure relevancy.

2.1.1. Inclusion and Exclusion Criteria

The inclusion of studies was determined by their pertinence to the fundamental subjects of membrane technologies employing smart materials in water treatment, adsorption, and photocatalysis. To ensure quality and impact, only open-access materials, peer-reviewed articles, and research with a citation count above a predetermined level were taken into consideration. Review articles, case studies, and experimental investigations were included to provide a balanced viewpoint. Excluded were studies with no empirical support or those irrelevant to the main topic. High-caliber, influential publications were prioritized with the aid of quantitative metrics like impact factors and recent citation counts.

2.1.2. Data Extraction and Analysis

After being chosen, the references were sorted by subject (such as environmental impact or adsorption efficiency) and examined for their contributions to sustainability, efficacy, and scalability in smart material water treatment applications. The uniqueness and rigor of each reference were assessed, with an emphasis on discoveries that furthered the discipline.

2.2. Stimuli-Responsive Polymers

"Smart polymers", also referred to as stimulus-responsive polymers, display alterations in their chemical or physical characteristics in response to external stimuli like light, pH, temperature, or electric fields. Because of their distinct behaviour, which allows them to be tailored to respond to the particular circumstances of a contaminated water source, they are extremely valuable for water treatment applications[7]. Temperature-responsive polymers, such as poly(N-isopropylacrylamide) (PNIPAM), have the ability to change their solubility or hydrophilicity through reversible phase transitions at crucial temperatures. This characteristic can be used to create cycle water treatment processes by trapping pollutants at specific temperatures and releasing them at different times. Similar to this, pH-responsive polymers, like polyacrylic acid, can expand or contract in response to the water's acidity or alkalinity. This property makes them useful for ensnaring contaminants like heavy metals and dyes, which have a tendency to bind at particular pH levels[8].

Due to their capacity to be precisely controlled in how they react to external stimuli, these polymers are especially appealing. For instance, researchers can increase the polymer's selectivity for particular contaminants, including metal ions or organic pollutants, by adding functional groups to its structure[9]. Moreover, stimuli-responsive polymers can be included in hydrogels or membranes to increase the surface area available for adsorption of pollutants and to provide better control over filtration procedures. Their dynamic nature makes it possible to create "smart filters" that instantly adjust to the circumstances of the water, improving the overall effectiveness of water purification. The widespread use of stimuli-responsive polymers is still relatively new; despite these benefits, durability, expense, and the possible environmental effects of polymer degradation products continue to be important study topics. The stimuli-responsive polymers are depicted in **Figure 1** below.

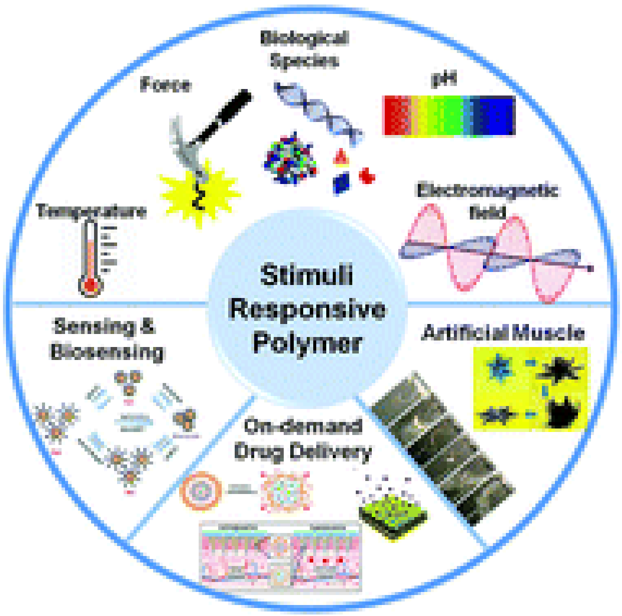

Figure 1. Stimuli-responsive polymers[10].

2.3. Nanocomposites

Nanocomposites, a new frontier in smart water treatment technologies, are materials composed of nanoparticles mixed with other materials like polymers or metal-organic frameworks (MOFs). As shown in below **Figure 2**, the remarkable characteristics of nanoparticles, including their huge surface area, high reactivity, and capacity to be functionalised with chemical groups that improve their interaction with contaminants, are advantageous to these materials. For example, nanocomposites based on graphene oxide have demonstrated remarkable antibacterial and heavy metal adsorption capabilities, such as lead, arsenic, and cadmium[11]. Effective removal from water is made possible by the high surface area of graphene oxide and its strong interactions with metal ions due to the presence of functional groups. Similar to this, when exposed to light, metal oxide nanoparticles such as zinc oxide (ZnO) and titanium dioxide (TiO_2) can break down organic pollutants by photocatalysis, converting dangerous substances including industrial chemicals, insecticides, and medications into less dangerous byproducts[12].

In addition to photocatalysis and the removal of heavy metals, nanocomposites can be designed to target a variety of contaminants. For example, carbon nanotubes (CNTs) have been added to nanocomposites to improve their mechanical strength, adsorption capabilities, and conductivity. These characteristics are especially helpful in the removal of harmful organics, oil, and organic dyes from water. Furthermore, the efficiency and selectivity of conventional polymer matrices and membranes can be greatly increased by adding nanomaterials[13]. For instance, the antifouling characteristics of nanocomposite membranes can stop the accumulation of bacteria, organic matter, or other pollutants, which usually reduces the efficiency of conventional filtration systems. Even though nanocomposites have many benefits, there are still a lot of unanswered questions about their scalability and potential toxicity. It is necessary to conduct additional research to determine the safe use of these materials in water treatment systems because the release of nanoparticles into the environment, either during use or after disposal, poses possible ecological and health hazards.

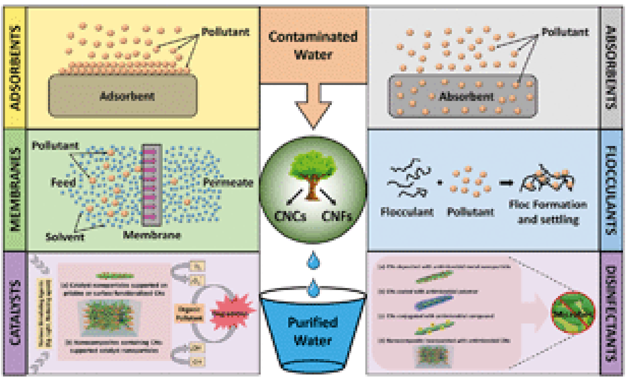

Figure 2. Nanocomposite material for water treatment[14].

2.4. Biomaterials

In water treatment, biomaterials like alginate, chitosan, and cellulose derivatives are being utilised more and more as environmentally friendly substitutes. These substances are non-toxic, biodegradable, and frequently show a great affinity for contaminants. For example, chitosan-based polymers have demonstrated excellent performance in eliminating heavy metals from contaminated water, such as lead and copper. Additionally, adding functional groups or nanoparticles to biomaterials improves their capacity to remove pollutants, which makes them perfect for usage in environmentally sensitive locations[15].

3. Mechanisms of Water Purification Using Smart Materials

3.1. Adsorption

One of the most popular methods for purifying water is adsorption, which works especially well when smart materials like stimuli-responsive polymers and nanocomposites are utilised. Pollutants adhere to the surface of the adsorbent material through the process of adsorption, which successfully removes pollutants from water. Because of their enormous surface area, functional groups, and capacity to be customised for particular pollutants, smart materials improve this process[16]. For instance, graphene oxide nanocomposites are extremely effective adsorbents due to their large surface area and abundance of oxygen-containing functional groups that form strong interactions with metal ions such as lead, arsenic, and mercury. Comparably, because of their special surface chemistry and structural features, functionalised carbon nanotubes (CNTs) have a high adsorption capacity for organic contaminants like dyes and medications[17].

Selectivity is a major benefit of employing smart materials for adsorption. Pollutants can be targeted by altering the surface chemistry of adsorbent materials. For instance, adding hydrophobic groups to nanomaterials might increase their affinity for organic pollutants, whereas adding amine or thiol groups can improve the adsorption of metal ions[18]. Furthermore, stimulus-responsive polymers can change their conformation in response to outside stimuli like temperature or pH, which allows for the regulated adsorption and release of contaminants. This reversible behaviour makes the process more sustainable by enabling the regeneration and reuse of the adsorbent material in addition to increasing efficiency. Scaling up these technologies, however, still presents difficulties because the regeneration process can occasionally cause a material's efficiency to deteriorate over time and because synthesising highly functionalised materials is still expensive[19].

3.2. Catalysis

Utilising smart materials for water purification also requires the critical mechanism of catalysis, specifically photocatalysis. Reactive oxygen species (ROS) are produced in photocatalytic reactions when light, usually ultraviolet (UV) light, activates materials like zinc oxide (ZnO) or titanium dioxide (TiO_2). These ROS, which have great oxidative potential and can decompose complex organic contaminants into simpler, less hazardous molecules, include hydroxyl radicals and superoxide anions[20]. Pesticides, medications, and industrial chemicals are just a few of the many organic pollutants that photocatalysis is quite good at degrading. TiO_2 is one of the most researched photocatalysts because of its capacity to produce ROS under UV light, chemical stability, and lack of toxicity. In an effort to increase photocatalytic activity and decrease energy consumption, researchers are also looking into the usage of doped TiO_2 and other modified materials[21].

In addition to photocatalysis, smart materials can function as catalysts in various advanced oxidation processes (AOPs) that produce reactive oxygen species (ROS) by chemical agents or electrical fields, like Fenton reactions and electrochemical oxidation. These procedures have the ability to break down viruses, inorganic pollutants like cyanide and ammonia, as well as organic pollutants. Due to their large surface area and capacity to aid in electron transport during the process, nanomaterial-based catalysts—particularly those that include noble metals like silver or gold—have shown improved catalytic performance[22]. Furthermore, it is possible to create intelligent catalytic materials that react to external stimuli, enabling the on-demand activation of catalytic processes in response to the detection of particular contaminants. However, despite catalytic systems' high efficiency, their wider implementation in water treatment is limited by issues such as catalyst deactivation, the production of potentially hazardous byproducts, and the expense of synthesising high-performance catalysts[23].

3.3. Membrane Filtration

The incorporation of smart materials has greatly improved membrane filtration, a popular method for treating water. Reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF) are examples of traditional membrane technologies that frequently experience problems including membrane fouling, which is the buildup of impurities on the membrane surface that lowers efficiency[24]. Smart membranes provide an answer by dynamically changing their characteristics in response to external stimuli. This is especially true of those made of stimuli-responsive polymers and nanocomposites. Temperature-responsive membranes, such as those composed of polymers like poly(N-isopropylacrylamide) (PNIPAM), are able to adapt to varying temperatures by changing the size of their pores. This enables the membrane to filter substances more effectively by focusing on the specific pollutants that are present.

In a similar vein, pH-responsive membranes can adjust their surface charge in response to the water's acidity or alkalinity, which enhances the elimination of charged contaminants like metal ions and dyes[25].

Smart membranes can have antifouling qualities in addition to their dynamic filtering abilities, which are crucial for preserving the filtration system's long-term effectiveness. The accumulation of organic matter, bacteria, or other impurities that usually result in fouling can be resisted by nanocomposite membranes, which contain materials such as graphene oxide, carbon nanotubes, or silver nanoparticles[26]. Silver nanoparticles, for instance, provide potent antibacterial qualities that hinder the formation of biofilms on the membrane surface, whereas carbon-based nanomaterials generate hydrophilic surfaces that ward against organic contaminants. Because of their ability to withstand fouling, membranes last longer and require less frequent cleaning or replacement, which lowers the cost of the filtration process. The environmental effects of nanomaterial leaking and the exorbitant expense of large-scale production of smart membranes are, nevertheless, causes for concern. For these materials to be widely used in water treatment systems, more research is required to increase their stability and safety. The review also considers traditional filtration techniques, such as reverse osmosis, nanofiltration, ultrafiltration, microfiltration, and particulate filtration, as illustrated in **Figure 3**, which depicts the filtration spectrum relative to the pore size of common materials

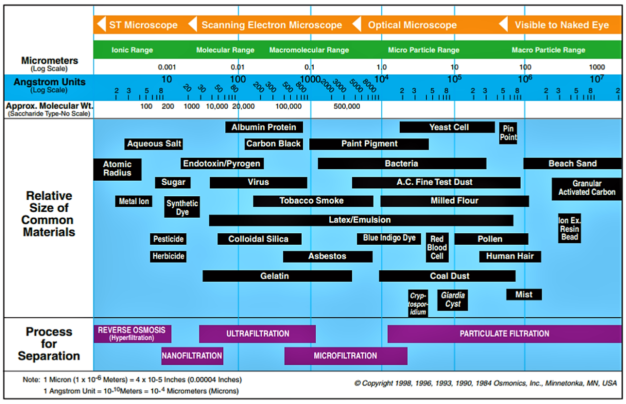

Figure 3. Filtration spectrum of reverse osmosis, nanofiltration, ultrafiltration, microfiltration and particulate filtration relative to the pore size of the common material[27].

4. Applications of Smart Materials in Water Treatment

4.1. Heavy Metal Removal

Lead, cadmium, mercury, and arsenic are just a few of the heavy metals that pose serious health hazards when found in drinking water, making heavy metal contamination an important global problem. Adsorbing these harmful elements has shown to be a very successful use of smart materials, especially nanocomposites and functionalised polymers. Metal-organic frameworks (MOFs), carbon nanotubes (CNTs), and graphene oxide (GO) are examples of nanomaterials with large surface areas and tunable functional groups that bond with metal ions selectively and facilitate their removal from contaminated water[28]. For instance, functionalised GO has shown remarkable adsorption capabilities for metals such as lead and mercury, whereby the presence of oxygen-containing groups on the GO surface amplifies metal binding.

The removal of heavy metals can be enhanced further by stimuli-responsive polymers, which modify their structure in response to changes in water parameters like pH. By capturing metals in acidic water and releasing them when the pH changes, pH-responsive materials allow for controlled cycles of metal adsorption and desorption. Because of their reversibility, the materials may be recycled and renewed, which lowers their cost and benefits the environment. Notwithstanding their potential, additional research is necessary to fully understand the scalability, long-term stability, and possible environmental hazards of nanomaterial leaching in order to maximise its large-scale applicability[29, 30].

4.2. Pathogen Removal

Another major issue with water treatment is pathogen contamination, especially in places with poor sanitary infrastructure. AgNP-embedded polymers and nanocomposites are examples of smart materials with potent antibacterial capabilities that can efficiently kill or inactivate pathogens including Vibrio cholerae, Salmonella, and Escherichia coli. AgNPs in particular produce silver ions that are particularly effective at disinfecting water because they can damage microorganism DNA, break bacterial cell membranes, and impede enzyme performance. By adding these substances to coatings or membranes, pathogens can be captured and neutralised while water flows through them[31].

Apart from nanoparticles, photocatalytic materials such as TiO_2 nanoparticles also work well for eliminating pathogens. Reactive oxygen species (ROS), which are produced when TiO_2 is exposed to light, have the ability to kill virus particles and bacteria. Since sunlight is all that is needed to initiate the disinfection process, this approach is especially beneficial in rural or resource-poor places. Even though these materials work well, more research is necessary to address concerns about nanoparticle leaching and the possible emergence of bacterial resistance to nanoparticles for long-term usage in pathogen eradication[32].

4.3. Organic Pollutant Degradation

Pesticides, medications, and industrial chemicals are examples of organic pollutants that are common in water systems and can be detrimental to the environment and human health. Ingenious materials are essential for breaking down these organic molecules, particularly photocatalysts like zinc oxide (ZnO) and titanium dioxide (TiO_2). These materials produce reactive oxygen species (ROS) when exposed to light, which can decompose complex organic compounds into less toxic byproducts like carbon dioxide and water. Numerous organic pollutants, including endocrine-disrupting substances and persistent organic pollutants, can be effectively removed by photocatalytic degradation[33, 34].

In addition to photocatalysis, clever adsorbents such as nanocomposites and functionalised polymers aid in the elimination of organic pollutants by binding to them and trapping them chemically. Hydrophobic nanocomposites, for instance, have the ability to adsorb organic substances, such as colours and oil-based contaminants, keeping them out of water systems. By incorporating these intelligent materials into water treatment procedures, organic pollutants can be continuously degraded or captured, minimising the negative effects of industrial and agricultural runoff on the environment. For widespread adoption, however, issues like the price of creating sophisticated photocatalysts and the creation of intermediate byproducts during degradation must be resolved[35, 36].

5. Scalability and Environmental Impact

5.1. Scalability

One of the biggest challenges to the successful application of smart materials in water treatment is scalability. Large-scale deployment of these technologies is fraught with challenges, despite laboratory-based research demonstrating exceptional efficacy in removing contaminants like viruses, organic pollutants, and heavy metals. The development of smart materials, particularly stimuli-responsive polymers and nanocomposites, can be expensive and require complex production processes. For instance, the cost of producing high-performance nanomaterials on a wide scale, like metal-organic frameworks (MOFs) or graphene oxide, is high since it requires sophisticated machinery and chemicals. Additionally, these materials' ability to retain their structural integrity and functionality over time—especially in the face of shifting climatic conditions—is crucial to their sustainability in actual water treatment systems[37].

The creation of graphene oxide water filtration membranes is one example of scaling smart materials. Researchers have successfully created these membranes in pilot-scale projects by employing a layer-by-layer technique that enables exact control over membrane characteristics. For instance, it has been demonstrated that adding nanoscale flaws improves permeability while preserving selectivity for a range of pollutants. Ongoing research is concentrated on streamlining the synthesis process to enable cost-effective scaling without sacrificing material integrity, as there are still difficulties in guaranteeing consistent quality and performance at higher production volumes[38].

Another scaling issue is the integration of smart materials into the existing water treatment infrastructure. Conventional filtration techniques like reverse osmosis (RO) or ultrafiltration may require extensive modification in order to incorporate smart membranes or catalytic systems. This may need developing entirely new systems or modifying current ones in order to properly exploit smart materials. Smart material regeneration and reuse, particularly in adsorption processes, must also be improved to ensure cost-effectiveness. Stimuli-responsive polymers, for example, can undergo multiple cycles of adsorption and desorption; but, the regeneration efficiency may deteriorate over time, requiring the materials to be periodically replaced or refunctionalized. In addition to ongoing research into more cost-effective production methods, material scientists and engineers will need to work together to develop systems that can use smart materials on an industrial scale in order to address these scaling challenges[39].

5.2. Environmental Impact

Although smart materials provide interesting approaches to water purification, it is important to carefully consider how they may affect the environment, particularly when it comes to nanoparticles. The release of nanoparticles like graphene oxide, carbon nanotubes (CNTs), or metal nanoparticles (like silver or titanium dioxide) could pose risks to human health and the environment. For instance, nanoparticles can build up in aquatic settings and may have an effect on aquatic microbes, plants, and animals. Studies have shown that nanoparticles can disrupt the biological processes of aquatic creatures, perhaps leading to toxicity or bioaccumulation in the food chain. Therefore, careful assessment of nanomaterial leaching during water treatment operations is essential to prevent unintended environmental contamination[40].

Furthermore, from production to disposal, the full life cycle of smart materials may have an impact on the environment. The long-term viability of these technologies is called into doubt because the synthesis of stimuli-responsive polymers and nanomaterials usually entails energy-intensive processes and the usage of hazardous chemicals. The long-term environmental effects of these compounds are also unknown, particularly once they are utilized in water treatment. Degradation products of polymers or nanocomposites might bring new contaminants into water systems if they are not managed properly. To reduce these hazards, research into biodegradable and ecologically safe smart materials is gaining momentum. By researching the use of naturally occurring materials such as biopolymers or plant-based adsorbents and creating green synthesis methodologies, smart water treatment systems can be made more sustainable and ecologically friendly[41].

6. Future Directions and Challenges

The desire for more effective, flexible, and long-lasting solutions to the problems associated with water contamination around the world is propelling the fast evolution of the field of smart materials for water treatment. To fully utilise the promise of these technologies, a number of issues and future directions must be addressed despite notable achievements.

6.1. Future Directions

(1) Integration of Multi-Functional Smart Materials: Creating smart materials that integrate several functions into a single system is a promising avenue. For instance, combining antibacterial, catalytic, and adsorption capabilities into a single material could result in extremely adaptable water treatment systems. These materials would provide a complete approach to water filtration, not just by capturing and breaking down contaminants but also by preventing the formation of pathogens. To improve overall performance, researchers are looking into composite materials that contain different active ingredients, like photocatalysts and adsorption sites[42].

(2) Advancements in Responsive Materials: It is imperative to design and synthesise stimuli-responsive polymers and nanocomposites with improved stability and responsiveness. Future studies should concentrate on making these materials more sensitive to outside stimuli like light, pH, and temperature while maintaining their long-term performance and robustness. Technological advancements in responsive materials may result in more flexible and effective water treatment systems that can adjust dynamically to changing water conditions, maximising the removal of contaminants[43].

(3) Sustainable and Green Chemistry Approaches: A growing number of people are interested in creating eco-friendly smart materials by applying the concepts of green chemistry, with a focus on sustainability. This covers the application of non-toxic synthetic techniques, biodegradable polymers, and renewable resources. Utilising natural resources, such as biopolymers or molecules produced from plants, to generate environmentally friendly substitutes for conventional synthetic materials is the main focus of research. This strategy seeks to guarantee the safe disposal or recycling of water treatment technology while lowering their ecological footprint[44].

6.2. Challenges

(1) Scalability and Economic Viability: One of the biggest obstacles still facing the development of smart materials is getting them from the lab to the industrial scale. It is necessary to overcome the high cost of synthesis and associated inefficiencies in large-scale applications. The wider implementation of smart materials depends on the development of efficient production processes, the enhancement of material performance, and the incorporation of smart materials into the current water treatment infrastructure. To show that these technologies are viable on a broader scale, investigations of economic feasibility and pilot projects are required[45].

(2) Environmental and Health Impacts: Comprehensive research is necessary to determine the possible effects of smart materials, especially nanomaterials, on the environment and human health. Risks to human health and ecosystems could arise from the usage or disposal of nanoparticles that are released into the environment. To reduce negative impacts, in-depth research on the toxicity, life cycle, and environmental fate of these compounds is necessary. Minimising possible risks requires developing safer nanomaterials, putting in place appropriate disposal procedures, and making sure regulations are followed[46–48].

(3) Regulatory and Standardization Issues: Standardised testing procedures and well-defined regulatory frameworks are necessary for the development and application of smart materials in water treatment systems. To ensure regulatory approval and consumer confidence, standards for material safety, efficacy, and environmental impact must be established. Establishing comprehensive stan-

dards that tackle the various applications and possible hazards linked to smart materials requires cooperation among researchers, policymakers, and industry stakeholders[49, 50]. This comparative **Table 1** for summarizes the main features of the primary biomaterials, nanocomposites, and stimuli-responsive polymers covered in the review, including their benefits, drawbacks, scalability, and costs.

Table 1. Comparative analysis of biomaterials, nanocomposites, and stimuli-responsive polymers in water treatment applications[51].

Material Type	Advantages	Disadvantages	Scalability	Costs
Biomaterials	Biodegradable and environmentally friendly Derived from natural sources (e.g., cellulose, chitosan)	Limited durability and resistance to chemical degradation Lower adsorption efficiency compared to synthetic materials	Scalable with low environmental impact, but requires optimization for stability in industrial applications	Generally low; depends on source and processing
Nanocomposites	High surface area for enhanced adsorption Tailorable for specific contaminant removal (e.g., heavy metals, organic pollutants)	Potential environmental risks due to nanoparticle release Expensive and energy-intensive synthesis	Moderate scalability; complex synthesis and disposal concerns limit widespread adoption	High; includes costs for production and disposal
Stimuli-responsive polymers	Adaptable to external stimuli (e.g., pH, temperature) Reusable and effective for selective contaminant removal	Decreased efficiency over repeated use cycles Requires precise environmental conditions for optimal functionality	Limited scalability; sensitive to environmental variations and challenging to integrate with existing systems	Moderate to high; costly to develop and maintain

7. Conclusions

Smart materials offer improved sustainability, adaptability, and efficiency in dealing with different contaminants, and they have the potential to completely transform the water treatment industry. Their special qualities allow them to effectively remove viruses, heavy metals, and organic contaminants from water. These qualities include their high surface area for adsorption, reactivity to environmental stimuli, and photocatalytic capabilities. These developments represent a major step forward in the creation of more adaptable and powerful filtration systems, designed to address a variety of problems with water quality.

But in order to fully utilise smart materials, a number of obstacles must be overcome, including those related to scalability, affordability, and environmental impact. Creating cost-effective production techniques, guaranteeing material safety, and incorporating new technologies into the current treatment infrastructures are all necessary to address these problems. The development of responsive technologies, the creation of multifunctional materials, and the adoption of ecologically friendly practices should be the main areas of future research. To progress these technologies and guarantee that they minimise dangers and have a minimal environmental impact while effectively contributing to global water purification efforts, cooperation between researchers, industry professionals, and policymakers is important.

Author Contributions

R.N. contributed to the conceptualization of the study, while N.M.S.Q. handled the technical aspects. Validation was performed by A.A.J., D.S.M.S.A.-K., and L.A.A.A. The work was proofread by M.A.A.Q., and N.M.S.Q. provided the necessary resources.

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Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. All relevant data are included in the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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