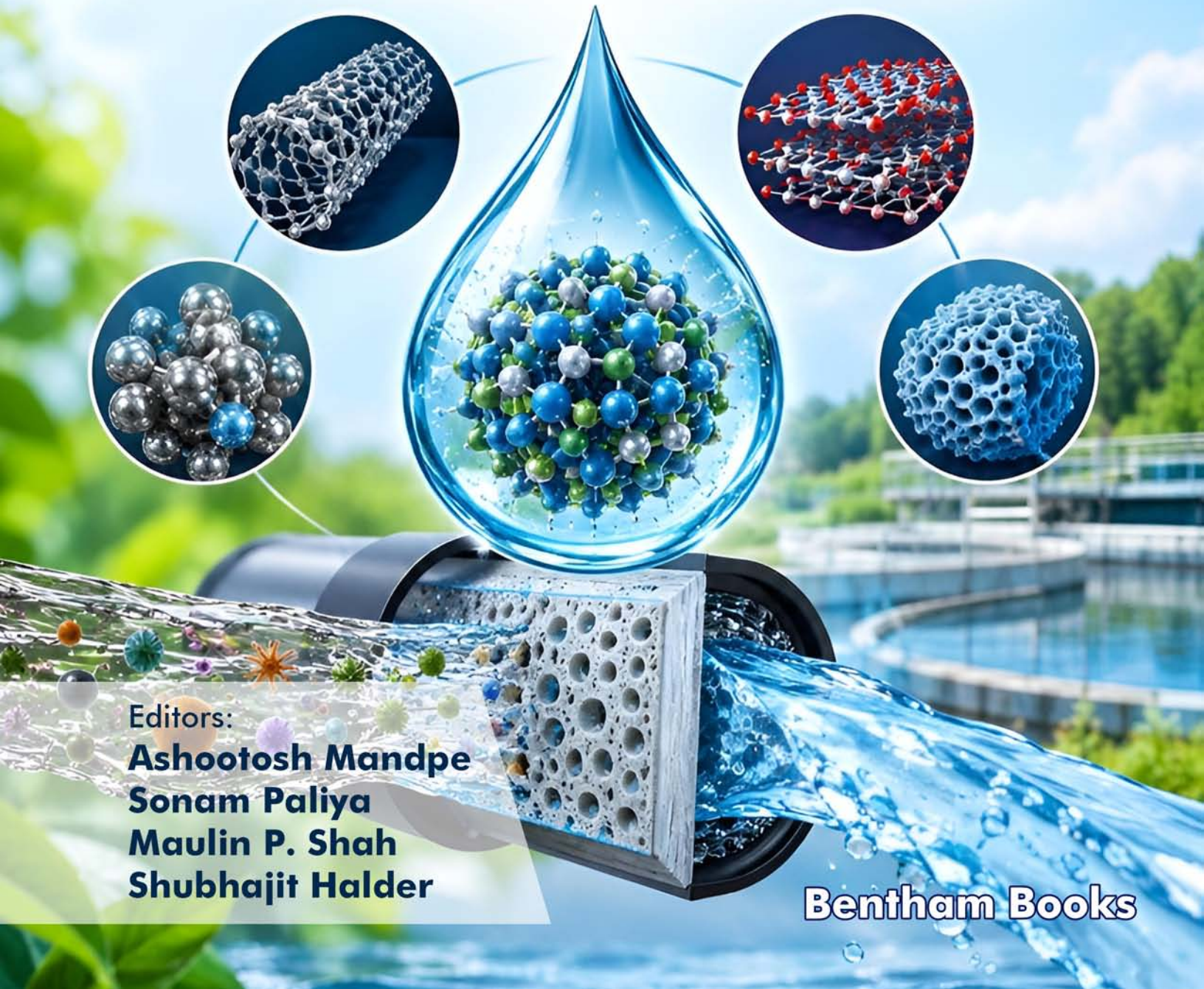
NANOMATERIALS
FOR
WATER TREATMENT
FUNDAMENTALS AND RECENT ADVANCES



Editors:
Ashootosh Mandpe
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PREFACE

Water is the essence of life, yet access to clean and safe water remains a global challenge. Rapid industrialization, population growth, and environmental degradation have exacerbated water pollution, necessitating advanced treatment methods. In response, nanotechnology has emerged as a transformative approach in water treatment, offering highly efficient, sustainable, and cost-effective solutions. This book, Nanomaterials for Water Treatment: Fundamentals and Recent Advances, delves into the role of nanomaterials in addressing contemporary water purification challenges, bridging the gap between fundamental science and practical applications.

The book is structured to provide an in-depth understanding of the different types of nanomaterials and their applications in water treatment. The opening chapter, Sustainable Water Treatment Solutions: The Role of Green Nanotechnology in Enhancing Purification Processes, highlights the integration of environmentally friendly nanotechnologies in water purification. Subsequent chapters explore specific classes of nanomaterials, including Organic Nanoparticles for Water Treatment and Metal and Metal Oxide Nanomaterials for Water Treatment, showcasing their potential for contaminant removal.

Advancing the discussion, Harnessing Metal and Metal Oxide Nanomaterials for Clean Water Technologies elaborates on their mechanisms and efficiencies. The advantages of polymer-based nanomaterials are presented in Polymer-Based Nanomaterials in Water Treatment, emphasizing their adaptability and multifunctionality. Moreover, Functional Nanomaterials for Water Treatment provides insights into customized materials designed for specific contaminants.

Industrial wastewater treatment remains a critical concern, addressed in Industrial Wastewater Treatment and Sustainable Technology for Aquatic Microplastic/Nanoplastics Remediation, which discuss innovative strategies for mitigating environmental hazards. Design of Nanocomposites for Water Treatment explores hybrid materials with enhanced capabilities, while Magnetic Nanoparticles for Separation of Water Pollutants focuses on their efficiency in pollutant removal through magnetic recovery techniques.

Photocatalysis, a breakthrough in water treatment, is examined in Photocatalysis: Effective Method for Wastewater Treatment and Photocatalysis in Water Treatment: A Sustainable Approach, shedding light on its role in degrading organic pollutants. The ecological impact of nanomaterials is addressed in Effect of Nanoparticles in Maintaining the Biological Ecosystem in Water, ensuring a balance between technological advancements and environmental sustainability.

Finally, Future Trends in Nanomaterials for Water Treatment: A Patinformatics Analysis offers a forward-looking perspective, analyzing emerging innovations and trends in the field. This book serves as a valuable resource for researchers, environmental scientists, and policymakers, providing a comprehensive overview of nanotechnology-driven solutions for water purification. We hope it inspires further research and innovation toward achieving global water security.

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CHAPTER 1

Use of Organic Nanoparticles for Water Treatment

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Abstract: A sufficient supply of drinkable water for human consumption is disrupted by environmental contamination in numerous ways. Various strategies are being used to address water shortage, but none are compelling enough to supply sufficient usable water. Developing innovative technology to solve this global problem is a formidable task for scientists, researchers, and enterprises. As a result, new and improved technologies and techniques are continually being developed to combat this threat. Among the several technologies at our disposal, nanotechnology offers a remarkable approach to purifying water. Nanomaterials can eliminate harmful organic pollutants, pathogens, microorganisms, heavy metal ions, anions, and other persistent contaminants from water sources because of their advanced production and precisely controlled pore sizes. This technology has outperformed other current strategies in the market due to its minimal use of nanomaterials to remove water pollutants effectively. Carbon-based organic nanomaterials possess exceptional physical and chemical properties due to the structure and expanding hybridisation of their constituent atoms. Single-walled carbon nanotubes (SWCNTs), multi-walled carbon nanotubes (MWCNTs), carbon dots, fullerenes (C_{60}, $C_{540)}$, graphene, and others are examples of well-known nanostructures composed of carbon atoms. Carbon dots are the most commonly used nanomaterials because they are less expensive to operate, biocompatible, and have low toxicity. The many benefits of biopolymeric nanomaterials, including their high adsorption capacity, low toxicity, biodegradability, and biocompatibility, make them suitable for effective water filtration. Furthermore, nanobiohybrid materials are essential for wastewater treatment and water purification. This chapter highlights the recent development and use of reasonably priced organic nanomaterials to purify water and produce safe drinking water.

Keywords: Adsorption, Biocompatibility, Contaminants, Nanomaterials, Organic nano-materials, Water purification.

INTRODUCTION

The existence of life on Earth cannot be explained by anything other than water, and drinking water is essential to human survival. One of the major concerns in

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the world today is water contamination. The primary cause of this water pollution is improper pretreatment of industrial waste, sewage waste, radioactive waste from nuclear power plants, garbage dumping, *etc.* [1]. A recent study found that around 80% of all industrial effluents and municipal wastes are disposed of improperly, directly or indirectly contaminating the water supply [2]. Furthermore, water resources are becoming alarmingly contaminated due to severe environmental contamination caused by natural and artificial activities. Water contamination creates a shortage of safe drinking water and poses a significant risk to human health. The need for drinkable water is constantly growing. The world's population growth and climate change are closely linked to the rising demand for water worldwide. The need for fresh water would increase sharply as the world's population is expected to nearly double from 3.4 billion in 2009 to 6.3 billion in 2050 [3]. According to a recent United Nations (UN) report, providing a sufficient quantity of fresh, clean water for the survival of all living things on Earth has become a global concern in the twenty-first century [4]. A recent WHO (World Health Organisation) research states that water contamination and the harmful effects of water pollution cause around 1.7 million deaths and 4 million serious illnesses each year [5]. The many types of water contaminants are listed in Table **1**, along with their sources and associated harmful health effects.

Table 1. Different kinds of water pollutants, their sources, and related adverse health issues.

Water Contaminants	Sources Contaminants	Adverse Effects	Refs.
Agricultural Pollutants	Agricultural chemical wastes	Directly affect the fresh water resources	[6]
Sewage and contaminated water	Domestic Wastewater	Waterborne diseases	[7]
Industrial Pollutants	Municipal pollutant Water	Caused water and air pollution	[8]
Radioactive Pollutants	Different Isotopes	Bones, teeth, skin, and can cause	[9]
Pathogens	Viruses and bacteria	Waterborne diseases	[10]
Sediments and suspended solids	Land cultivation, demolition, mining operations	Damaging fish spawning, affecting aquatic environment of insects and fishes	[11]
Inorganic Pollutants	Metal compounds, trace elements, inorganic salts, heavy metals, mineral acids	Aquatic flora and fauna, Public Health problems	[12]
Organic Pollutants	Detergents, Insecticides, Herbicides	Aquatic life problems, Cacogenic	[13]
Macroscopic Pollutants	Marine debris	Plastic pollution	[14]

When undesirable substances from various sources enter water systems and reservoirs, they contaminate the water and render it unfit for human consumption and other uses. The primary pollutants in contaminated water are organic and inorganic compounds, microorganisms, and specific heavy metals (such as Pb, Mo, As, and Hg) that have released into the water stream from various sources. Different physical, chemical, and mechanical techniques are available to effectively remove these toxic chemicals from polluted water to make it drinkable. Moreover, the search to develop more improved, sustainable, and cost-effective technologies for efficiently purifying water contaminants is an encouraging and emerging field of new research [15]. Due to the recent advancements in nanoscience and technology, nanotechnology has emerged as a superior alternative to conventional approaches for water purification [16].

Different Types of Nano-materials

Materials with dimensions in the range of 1-100 nm are generally considered nanomaterials (NMs) [17] (Fig. **1**). Nanomaterials behave differently from bulk materials because of their enormous surface area. The following is a classification of the nanostructured materials based on their dimensions [18].

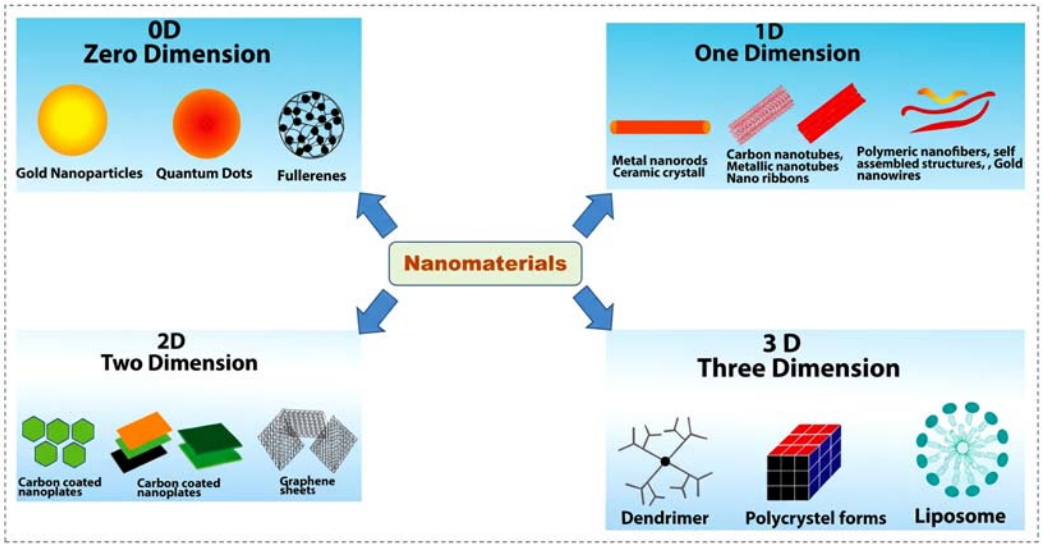


Fig. (1). Different kinds of nanomaterials.

i. Zero dimension (0-D) NMs [*e.g.,* quantum dots (QDs)]
ii. One dimension (1-D) NMs [*e.g.,* nanowires, nanorods, nanotubes, *etc*.]
iii. Two-dimensional NMs (2-D) [*e.g.,* nanoplates, nanodisks]
iv. Three-dimensional NMs (3-D) [*e.g.,* nanoflowers, nanocoils, nanoballs, *etc*.]

CHAPTER 2

Harnessing Metal and Metal Oxide Nanomaterials for Clean Water Technologies

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Abstract: Water scarcity and conservation have become critical worldwide, as water is a vital yet limited resource. Water quality is declining every day due to anthropogenic activities and the rapid growth of the human population. Clean water technologies are crucial for treating wastewater, removing toxic contaminants and hazardous pollutants, and ensuring safe drinking water and sustainable water management. Water purification technologies involve the removal of soluble and insoluble organic, inorganic, and biological pollutants. It makes water reusable and suitable for various applications, including drinking, agriculture, and industrial use. Recent research has shown that nanotechnology can be used as an economical and sustainable approach to treat water and wastewater. Moreover, nanomaterials have great potential to effectively remove various pollutants (organic and inorganic) and toxic heavy metals. Metal oxide nanoparticles serve as a fundamental stepping stone for the development of functional nanomaterials with various applications and as promising, affordable, and efficient materials for water treatment. Furthermore, metal and metal oxide nanomaterials have large surface areas, superior adsorption capacity, heavy-metal selectivity, photocatalytic activity, and antibacterial and antifungal properties. These nanomaterials demonstrate improved efficiency, reduced energy consumption, and greater potential for water reuse and recycling.

Keywords: Adsorption, Clean water, Disinfection, Filtration, Harnessing, Heavy metals, Inorganic pollutants, Membrane, Metal, Metal oxide.

INTRODUCTION

Water is an essential factor for supporting diverse life forms on Earth. It is a vital component that is necessary for the survival of biological species, responsible for

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health, biodiversity, and the functioning of ecosystems. [1] However, water scarcity and water conservation have become serious global issues, as humanity faces many obstacles in ensuring everyone has access to clean water. Global warming and population growth have further stressed already overburdened water systems, especially in developing regions [2]. Water quality is declining every day due to anthropogenic activities and the rapid growth of human population [3]. The urgency of developing advanced water treatment technologies has never been more critical, as global water scarcity continues to escalate. With climate change intensifying droughts and unpredictable weather patterns, freshwater resources are becoming increasingly strained. Traditional water treatment methods are often insufficient to address complex contaminants, such as industrial waste, pharmaceuticals, and emerging pollutants. Furthermore, the current state of global water pollution underscores the need for urgent technological advancements.

Science and technology play a crucial role in providing clean water through various innovative solutions and approaches for drinking, irrigation, and other practices. But accessibility, affordability, sustainability, and the commercialisation of modern technology remain daunting challenges for the scientific community. The United Nations has established Sustainable Development Goal 6, "Clean water and sanitation," to ensure the accessibility of clean drinking water and acceptable sanitation and hygiene for everyone [4]. New water treatment technologies, such as advanced filtration systems, desalination processes, waste-to-water conversion techniques, and other clean water technologies, are essential to ensuring a sustainable, clean water supply. With these technologies, we can address both existing water quality issues and prepare for future challenges. Investing in research and development now will secure a cleaner, safer water supply for future generations.

Clean water technologies are crucial for treating wastewater, removing toxic contaminants and hazardous pollutants, and ensuring the provision of safe drinking water and sustainable water management. These technologies are essential for addressing global water scarcity and pollution issues, ensuring public health, and protecting ecosystems. Water purification technologies involve various processes (physical, chemical, and biological) for removing suspended and dissolved organic, inorganic, and biological contaminants. It makes water reusable for various purposes, such as drinking, industrial use, irrigation, and more [5]. Water purification techniques commonly available are filtration, ultrafiltration (UF), sedimentation, distillation, reverse osmosis (RO), flocculation and coagulation, UV-filtration, ion-exchange, chlorination, ozonation, activated carbon adsorption, deionization, use of water softeners for removal of heavy metals, *etc* (Fig. **1**). However, the main drawbacks of the aforementioned methods are the high operational and maintenance costs, high energy requirements, and the

need for substantially large plant areas. This emphasises the need for a technologically advanced, effective, and sustainable methodology for water purification and wastewater treatment processes.

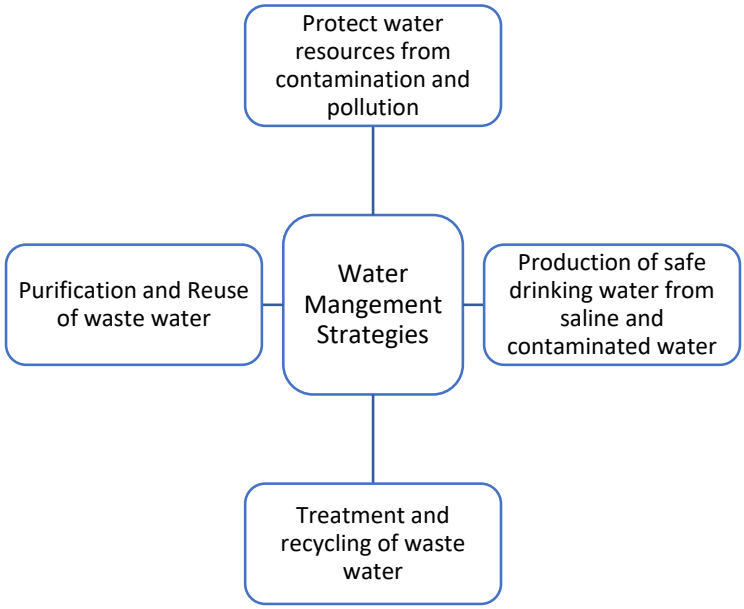


Fig. (1). Water management strategies.

Recent research has shown that nanotechnology can be used as an economical and sustainable approach to treat water and wastewater [6]. Nanotechnology can be harnessed as a transformative approach in clean water technologies, offering innovative solutions to enhance water purification, treatment, and management [7]. Nanomaterials are materials engineered at the nanometre scale, typically in the range of 1 to 100 nanometres (nm). The larger surface area and quantum effects impart nanomaterials with exceptional properties compared to their bulk counterparts. These properties can lead to enhanced reactivity, greater flexibility, size-dependent characteristics, and affinity for specific pollutants. Moreover, nanomaterials have great potential to remove a diverse range of pollutants from wastewater effectively [8]. Incorporating engineered and modified nanomaterials, such as carbon nanotubes (CNTs), activated carbon, polymers, and composite materials, into water treatment processes can enhance purification, disinfection, and contaminant removal (Fig. **2**). Nanomaterials such as nanosorbents, nanostructured catalytic membranes, nano-catalysts, and bioactive nanoparticles have been dynamically employed in wastewater treatment [9]. The current chapter illustrates recent trends in harnessing metal and metal oxide nanoparticles for the treatment and safe reuse of water and wastewater.

CHAPTER 3

Sustainable Technology for Aquatic Microplastic/Nanoplastic Remediation

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Abstract: Microplastics (MPs) and nanoplastics (NPs) have become prevalent contaminants in aquatic habitats, posing major threats to ecosystems and human health. Conventional remediation techniques often fall short in effectively removing these small plastic particles, highlighting the need for sustainable technological solutions. This chapter explores the development and application of sustainable methods for removing MPs and NPs from water. Innovative techniques that balance effectiveness with environmental responsibility are highlighted, including improved filtration, adsorption, catalytic degradation, and the integration of chemical and biological processes. The chapter also discusses the design principles behind sustainable remediation technologies, their real-world applications, and the environmental and societal implications of their deployment. In this context, the goal of this chapter is to outline the various origins of MPs, highlighting their impact on aquatic ecosystems and the threat they pose to human health, while reviewing the few sustainable material-based modeling studies that have been conducted to project the future contribution of plastic to the aquatic ecosystem. By addressing the challenges of scaling up and integrating these technologies into existing water treatment systems, this chapter provides an in-depth overview of the prospects and future directions for using sustainable remediation technologies to achieve environmental sustainability on a global scale.

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Keywords: Aquatic pollution, Environmental remediation, Microplastics, Nanoplastics, Sustainable technology, Water treatment.

INTRODUCTION

The synthetic or semisynthetic polymers that make up plastics are made up of long chains of carbon atoms, often with nitrogen and oxygen atoms mixed together. The global manufacturing of plastic has skyrocketed [1]. The exponential growth in worldwide plastic production has accelerated the discharge of plastic waste into the environment, posing potential threats and severe obstacles to water environmental safety [2]. Plastics decompose into little fragments rather than breaking down entirely since they are durable materials. They can cycle through aquatic systems, on land, and in the atmosphere, depending on the degree of deterioration. These broken-down particles are referred to as microplastics when they are smaller than 5 mm [3]. The term "nanoplastics" is applied to microplastics that undergo further degradation into particles with a diameter of 100 nm or less [4]. MP sources are divided into primary and secondary categories based on their origin. While primary microplastics are purposefully produced for use in household or commercial cosmetic products, secondary microplastics are generated in the environment as a result of physical processes and photo-oxidation that break down, alter, and degrade parent (micro)plastics [5, 6]. The presence and accumulation of microplastics in water is a major issue for several reasons, particularly because they are consumed by marine life. A major problem for MPs is their ability to adsorb other fundamental natural pollutants, such as heavy metals, cosmetics, pharmaceutical compounds, and so on; this can result in diseases, including cancerous growth, weakened immunity, and decreased reproduction in animals and humans [7]. The introduction of anthropogenic and natural toxins into water bodies has had a significant impact on their quality. The spread of MP/NP contamination has raised significant concerns due to its detrimental effects on living organisms.

Green, eco-friendly, and sustainable concepts have emerged in analytical chemistry in recent years. New materials and techniques are continually being researched to advance this field, which has led to significant technical innovation over the past several years. Nano-enabled technologies offer promising prospects for significant increases in monitoring, identification, characterization, detection limits, and elimination efficiency in the context of microplastic management and treatment [8].

SUSTAINABLE TECHNOLOGIES FOR REMEDIATION

Sustainable technologies aim to minimize environmental risks. Biological approaches to microplastic breakdown include the use of microbes, algal biofilms, and enzymes. Certain bacteria and fungi, like *A. xenomutans* and *H. titanicae*, degrade plastics into simpler, non-toxic components. Furthermore, enzymes such as PETases are used to accelerate the breakdown process. Physical approaches primarily focus on separation techniques that use enhanced filtration and adsorption. Microplastics are routinely separated using membrane filters, biochar, and magnetic particles, which readily adhere to them. Chemical approaches include processes that break down polymers into smaller molecules. Advanced Oxidation Processes (AOPs) use ozone or hydroxyl radicals, whereas photocatalysis uses light-driven reactions with catalysts like titanium dioxide [9].

Sustainable technologies, particularly biological ones, help to decrease pollution and improve ecological balance. They make use of renewable resources, making them both cost-effective and environmentally friendly. These methods are adaptable to a variety of environments, ranging from small-scale water treatment facilities to large-scale industrial applications. The performance of various sustainable technologies for the removal of microplastics and nanoplastics is summarized in Table **1**. They degrade microplastics into harmless chemicals, lowering threats to aquatic life and human health. They can also help the circular economy by reusing or recycling recovered plastics. Effective cleanup prevents microplastic buildup, protecting aquatic habitats and biodiversity [10].

Table 1. Summary of the removal of MPs/NPs by various sustainable technologies.

Sr. No.	Source	Technology	Material used	Type of Polymer	Removal Efficiency	Refs.
1	Marine water	Biodegradation (fungus)	*Zalerion maritimum*	Polyethylene (PE)	43%	[26]
2	Marine Water	Biodegradation (bacteria)	*Pseudomonas aestusnigri*	Polyethylene terephthalate (PET)	4.32 mg/ml	[27]
3	Marine Water	Biodegradation (bacteria)	*P. tetraodonis* and *P. lipolytica*	polystyrene (PS) and polypropylene (PP)	-	[28]
4	Sediment, wastewater, and activated sludge	Biodegradation (bacteria)	*Ideonella sakaiensis 201-F6*	Polyethylene terephthalate (PET)	75%	[15]

CHAPTER 4

Functional Nanomaterials for Water Treatment

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Abstract: Functional nanomaterials are nano-sized materials with unique properties that are used in advanced technologies, including water treatment. These minute materials can efficiently remove contaminants and improve water quality, making them an effective alternative to conventional water treatment methods. Functional nanomaterials in this chapter include metallic nanoparticles, metal oxides, carbon-based nanostructures, and polymeric nanocomposites that have unique physicochemical attributes such as high surface area-to-volume ratios, enhanced reactivity, and impressive surface functionalities, which can be applied to remove a wide and diverse range of contaminants, including heavy metals, organic pollutants, and microbial pathogens. Specific carbon-based nanomaterials, such as graphene oxide, exhibit high adsorption capacities for the capture of heavy metals and metal oxides, such as titanium dioxide, which is known for its photocatalytic properties and the ability to degrade organic pollutants under irradiation. Metallic nanoparticles, such as silver and copper, exhibit significant antimicrobial activity and are highly effective in disinfection and related processes. Functional nanomaterials are particularly effective against pathogens in water, as they prevent infections without affecting ecosystems. Despite promising capabilities, challenges remain regarding the scaling and economic feasibility of deploying functional nanomaterials for water treatment. The integration of functional nanomaterials with emerging technologies, smart sensors, and automated control systems may potentially enable adaptive water treatment solutions and highly efficient water treatment applications. As such, this chapter argues that research has been ongoing to develop functional nanomaterials that can enhance water treatment technologies cost-effectively, providing a long-term solution to water pollution.

Keywords: Antimicrobial activity, Contaminants, Functional nanomaterials, Pollution, Treatment, Water.

INTRODUCTION

Water pollution remains a global problem, with increased contamination by heavy metals, pesticides, pharmaceuticals, organic compounds, and pathogenic microor-

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ganisms, which degrade the quality and safety of water resources [1]. These contaminants originate from high levels of industrialisation, urbanisation, and agricultural activities, which later enter aquatic ecosystems, posing a severe threat to aquatic organisms and public health, as well as to the overall quality of drinking water, making it a serious matter requiring effective remediation solutions [2]. Heavy metals such as lead, cadmium, and mercury, as well as organic pollutants such as pharmaceuticals and pesticides, are not readily biodegradable and accumulate in water systems, disrupting aquatic ecosystems. With their persistence, they may enter and cause long-term adverse health effects [3, 4]. Pathogenic microorganisms pose another challenge, as they cause waterborne diseases, underscoring the need for efficient disinfection techniques [5]. Water treatment systems need new and efficient treatment technologies for the elimination of these emerging pollutants since conventional water treatment techniques, including coagulation, filtration, and chlorination, may not be useful in the removal of emerging contaminants such as microplastics, pharmaceuticals, endocrine-disrupting chemicals, pesticides, and heavy metals that continue to persist in the environment and pose risks in the future [6, 7]. While traditional methods have been deemed inadequate, water pollution has increased over the years. Hence, new advanced water treatment technologies need to be developed with efficient, sustainable mechanisms for safe, clean water, in which innovations in chemical, physical, and biological processes target the efficiency and sustainability of water purification to remove a wide spectrum of contaminants and minimise their effects on the environment. Advanced technologies such as membrane filtration, advanced oxidation processes, and biological treatments increase the precision of targeting specific pollutants [8]. Most dissolved solids, pathogens, and organic contaminants are effectively removed from water using membrane-based systems, such as reverse osmosis and nanofiltration [9]. AOPs employ reactive radicals, such as hydroxyl radicals, to decompose persistent organic pollutants into harmless by-products, thereby being applicable for the treatment of heavily polluted industrial wastewater [10]. Moreover, biological treatment technologies, such as activated sludge and biofilm reactors, have evolved, with microbial consortia genetically modified to degrade a wide range of pollutants [11]. However, although these technologies have been efficient, they also entail financial and operational disadvantages, including high energy consumption, maintenance costs, and complex waste management practices [8]. The integration of advanced water treatment methods with innovative materials, such as functional nanomaterials, has strong potential to increase efficiency and affordability while providing a more sustainable solution for future water treatment needs [12]. Recently, nanotechnology has introduced functional nanomaterials as a promising tool to overcome the limitations of conventional and advanced water treatment techniques, which have not achieved comparable

efficiencies in detecting, removing, and degrading various pollutants [13]. These materials, with their nanoscale dimensions and physicochemical properties, offer new opportunities to achieve enhanced contaminant removal efficiency. Their high surface area, increased reactivity, and ability to modify surface characteristics make them a good tool for targeting a wide range of pollutants with high accuracy [14]. Some categories of functional nanomaterials include metallic nanoparticles, metal oxide nanomaterials, and carbon-based nanomaterials, which can be used in water treatment and offer distinct advantages [15]. Scalability issues, economic viability, and environmental problems associated with the disposal of nanomaterials are key challenges hindering the widespread application of functional nanomaterials [17]. The interest in functional nanomaterials is increasing as research seeks to maximise their effectiveness while minimising risks.

This chapter focuses on the transformative potential of functional nanomaterials for water treatment, discussing their unique properties, mechanisms of action, and diverse applications. It involves understanding challenges and future perspectives in the field, and the significance of interdisciplinary collaboration in overcoming existing barriers and opening the door to wider use. The development of functional nanomaterials for water treatment can yield solutions that are efficient, sustainable, and economically viable to address the complex nature of modern water pollution. The contaminants in water are on the rise, including heavy metals, pesticides, pharmaceuticals, organic compounds, and pathogenic microorganisms; all of these affect the quality and safety of water resources [18, 1]. These contaminants have arisen mainly due to rapid industrialisation and urbanisation, as well as agricultural activities, which reach aquatic ecosystems and pose a serious threat to these organisms, public health, and the overall quality of drinking water, increasing the need for robust remediation solutions [19]. Heavy metals include lead, cadmium, and mercury, which are non-biodegradable, accumulate in water systems, disrupt ecosystems, and may contribute to long-term adverse health effects through their persistence and the potential for bioaccumulation [20, 21]. Other challenges posed by pathogenic microorganisms include water-related diseases, which require appropriate disinfection methods during treatment. Modern treatment systems for water treatment require efficient and innovative treatment technologies to remove these pollutants since conventional water treatment methods, such as coagulation, filtration, and chlorination, are often inefficient in removing emerging contaminants, including microplastics, pharmaceuticals, endocrine-disrupting chemicals, pesticides, and heavy metals, which persist in the environment with serious risks [6, 8, 20]. The issues, therefore, demand the development of advanced, efficient, and sustainable water treatment technologies to ensure a safe, clean water supply. With increasing water pollution, advanced water treatment technologies have emerged to address

CHAPTER 5

Use of Magnetic Nanoparticles for Separation of Water Pollutants

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Abstract: The sustainable growth of any society is directly proportional to the development of novel methods and technologies for managing environmental quality. Magnetic nanoparticles (MNPs) have attracted considerable attention in environmental remediation, particularly for treating water pollution, owing to their distinctive physical and chemical properties. Their large surface-area-to-volume ratio and adjustable magnetic characteristics facilitate the efficient adsorption and removal of a variety of contaminants, including heavy metals, organic and inorganic pollutants, anionic and cationic dyes, pharmaceutical products, and pathogenic microorganisms. These nanoparticles can be easily manipulated using external magnetic fields, facilitating their separation from water after treatment. Recent advancements focus on optimising the synthesis of magnetic nanoparticles to increase adsorption capacity, enhance stability and reusability, and functionalise them with specific ligands or coatings to target particular pollutants. It is reported that MNPs offer target specificity and cost-effectiveness compared to conventional treatments. This review examines the latest developments in the application of magnetic nanoparticles for water treatment, their mechanisms of action, performance in real-world applications, and future directions for research and implementation.

Keywords: Adsorption, External magnetic field, Magnetic nanoparticles, Pathogenic microorganisms, Water treatment.

INTRODUCTION

The most prevalent substance on Earth, water, is a necessary component of all living things. Water plays a vital role in carrying out daily tasks and is essential for sustaining life. The remarkable biological significance of water is demonstrated by the fact that it comprises between 60% and 95% of the mass of all living organisms. Water is the mother, the medium, the matrix, and the matter of life. Without water, life cannot exist. These days, national and international or-

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ganisations and governments are interested in water-related concerns such as resource depletion and drinking water quality [1].

Concerns about water scarcity have been increasing due to industrial development, climate change, and global population growth. It is anticipated that these issues will intensify in the coming decades, even in regions where this vital resource is currently relatively abundant. Therefore, it is imperative to explore new technologies to ensure a sustainable water supply and reduce pollution levels [2].

It was determined that nanoparticles have significant potential for use in novel water treatment procedures, enhancing the efficacy of water purification and augmenting water supply through the use of non-conventional, safe sources [3]. Recent developments in this field present opportunities to develop the next generation of water supply systems [4].

Nanotechnology offers cost-effective waste treatment processes with excellent performance and reduced reliance on large-scale infrastructure as an alternative to conventional centralised systems. Beyond their inertness, one of the most important benefits of using nanoparticles in water treatment is their suitability for point-of-use applications. This is compared with the majority of conventional water treatment methods, which are intended for centralised treatment plants. Advantages of nanomaterials include high specific surface areas, rapid dispersion, strong reactivity, and high absorption capacity for diverse organic contaminants, heavy metals, and microorganisms. However, unlike traditional chemical disinfectants, they are not expected to generate hazardous disinfection byproducts because they are not strong oxidants. Strong specific surface areas, quick dispersion, strong reactivity, and high absorption capacity for various organic contaminants, heavy metals, and bacteria are only a few of the numerous benefits associated with nanomaterials. However, unlike traditional chemical disinfectants, they are not anticipated to create hazardous disinfection byproducts because they are not strong oxidants [5].

Certain nanomaterials exploit their discontinuous properties, such as supermagnetism. The absorption capacity of magnetic nanoparticles (MNPs) increases with particle size.

Sources of Water Contamination

Although there are many sources of drinking water, the main ones are lakes, canals, reservoirs, rain, fog, and seawater. Although these sources are tainted in different ways, they can be roughly divided into two groups.

- Point sources or direct sources
- Non-point or indirect sources

Basically, effluent from factories, treatment facilities, refineries, and other industries is a direct source. On the other hand, contaminated water from indirect or nonpoint sources can enter a body of water through various pathways. For example, when pesticides and fertilisers are applied to agricultural fields, their components seep into groundwater and contaminate it.

Different Types of Water Contaminants

Although there are many different kinds of contaminants in water, organic, inorganic, and pathogenic contaminants are briefly covered in the subsections that follow.

Pathogenic Microorganisms

Even though pathogenic microorganisms like bacteria, viruses, and parasites can cause a variety of infectious diseases and are among the major threats to the safety of drinking water, they can be found at very low concentrations in water [6].

The primary sources of harmful bacteria in the aquatic environment are sewage discharges and wastewater from facilities such as slaughterhouses. Numerous disease outbreaks, including cholera, diarrhoea, and gastrointestinal illnesses, have been linked to water-borne microorganisms [7]. Numerous factors, including various forms of water contamination, population growth, modifications to potable water treatment techniques, and increased international trade and travel, contribute to the recurrence of water-borne diseases. Advanced techniques for source tracking and detection have significantly improved the identification of pathogen-driven water contamination [8, 9].

The consumption of water contaminated with faeces poses the greatest health danger, and the discharge of wastewater into natural water bodies promotes the growth and spread of pathogens [10].

Pharmaceutical Products

Pharmaceutical contaminants in water refer to the presence of pharmaceutical compounds in surface water, ground water, and drinking water. These contaminants often enter the water supply through various pathways, including:

Improper Disposal: Flushing unused medication down toilets or pouring it down drains contributes to pharmaceutical contamination.

CHAPTER 6

Photocatalysis: Effective Method for Water Treatment

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Abstract: Photocatalysis has gained considerable attention as an effective approach for water purification, utilizing light energy to degrade hazardous contaminants and microbial species. Semiconductor materials, particularly titanium dioxide (TiO_2), play a central role in this process by generating reactive oxygen species (ROS) upon light irradiation, which subsequently facilitate the decomposition of organic pollutants, heavy metals, and pathogenic microorganisms. Key advantages of photocatalytic treatment include its operation under relatively mild conditions with minimal chemical input, making it a more sustainable alternative to conventional water treatment technologies. Recent research has increasingly focused on the development of visible-light-responsive and nanostructured photocatalysts to improve overall efficiency and broaden practical applicability. This chapter examines the fundamental principles, operational strategies, and real-world applications of photocatalysis in water treatment systems, and addresses existing limitations. Despite its potential for complete mineralization and continuous disinfection, challenges such as catalyst stability, limited light absorption range, and issues related to large-scale implementation remain significant. Addressing these constraints through material optimization, hybrid system integration, and interdisciplinary approaches is essential to enhance economic feasibility and environmental sustainability. Consequently, photocatalysis represents a promising and evolving solution to meet the growing global demand for clean, safe water.

Keywords: Electron-hole pairs, Environmental impact, Photocatalysis, TiO_2, Water treatment.

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INTRODUCTION

Photocatalysis, which uses light irradiation to degrade pollutants in water, is considered a promising alternative for water treatment. These usually involve photosensitizers, which generate various reactive species once they are illuminated with light. Titanium dioxide (TiO_2) is one of the most widely studied and researched photocatalysts that operate under ultraviolet (UV) light. Its excellent stability, non-toxic nature, and strong oxidizability enable it to be widely used in environmental and energy applications [1-3]. The field was further broadened and now also includes visible-wavelength photoactive photocatalysts, such as metal oxide modifications and carbon-based materials, with recently enhanced performance under solar light. Photocatalysis has been widely developed because it generates electron-hole pairs in materials exposed to light. These pairs then combine with water and oxygen, yielding hydroxyl radicals and superoxide ions, reactive molecules that are very effective at breaking down contaminants. This technology has several advantages. It can fully break down contaminants, is used with little chemical input, and is targeted against a broad array of pollutants [4-6]. Some challenges include improving catalyst performance, maintaining long-term stability, and scaling up for real-world applications. However, ongoing research is making progress in overcoming these issues, paving the way for photocatalysis to become a reliable and sustainable water purification method [7, 8]. Water pollution caused by industrial activities, agricultural runoff, and household waste has increasingly become a significant global concern in recent years. While conventional water treatment techniques are effective, they often struggle with solid pollutants and require considerable resources. In response to these challenges, photocatalysis has emerged as a promising and sustainable approach for purifying water. This innovative technology offers a powerful alternative to address the pressing problem of water contamination. This chapter examines in detail the principles of photocatalysis, its applications in water treatment, and the development of its efficiency. Photocatalysis has emerged as a sophisticated method for treating water, using light energy to generate active chemicals that purify polluted water. This technique employs photocatalysts to promote reactions under mild conditions, with TiO_2 being one of the most commonly used semiconductor photocatalysts [9-11]. Conventional energy production and pollution are two areas of active research. Semiconductor-mediated photocatalysis is a promising technique for degrading pollutants to produce hydrogen, which is a readily available gas source. Photocatalysis can be described as a catalytic process that uses the absorption of light to activate a catalyst. The process has gained importance due to its efficiency in addressing environmental challenges and generating renewable energy [12]. NTO offers chemical and biological inertness, superior photostability compared to other semiconductor photocatalysts, and low manufacturing costs. Additionally,

NTO enables efficient photocatalytic purification of liquids and gases, making it a highly effective and environmentally friendly advanced oxidation process (AOP) [13-15]. Photocatalysis has emerged as an innovative and efficient approach for water purification, offering a sustainable solution to the growing problem of water pollution. In this process, light energy activates a catalyst, initiating a series of chemical reactions that generate highly reactive species such as hydroxyl radicals and superoxide ions. These reactive species play a crucial role in breaking down organic pollutants, toxic substances, and harmful microorganisms present in water. The overall process operates under mild conditions and does not require extensive chemical inputs, which enhances its efficiency and environmental compatibility. As a result, photocatalysis stands out as a promising technology capable of addressing global water contamination challenges. This chapter explores the fundamental principles, recent developments, and practical applications of photocatalysis in water treatment, highlighting its potential to influence environmental policies and contribute to the protection of clean water resources.

The process relies on photocatalytic materials, which speed up these reactions when exposed to light. These catalysts are typically semiconductor materials, such as TiO_2, which have the unique property of absorbing photons and emitting electron-hole pairs when activated by UV or visible light, and function as various highly reactive compounds, such as (•OH) and super-oxide ions ($•O_2^-$). These active species are particularly effective at breaking down a wide range of herbal contaminants into harmless compounds, including carbon dioxide and water. By disrupting the cell structures of microorganisms, they can also inactivate them [16-19]. Recent advances in photocatalytic membranes, particularly TiO_2-based systems, have shown significant potential for water treatment applications. The recent progress in TiO_2-based photocatalytic membrane systems for water purification is summarized in Table **1**, which outlines membrane configurations, fabrication approaches, and their corresponding performance under UV irradiation [20-23].

The main advantage of a photocatalyst is that it can operate under mild conditions, making it both energy-efficient and adaptable. Unlike conventional water treatment methods that often rely on high temperatures, chemicals, or significant energy consumption, photocatalysis works well at everyday temperatures and emphasizes that it not only reduces operating costs but also the environmental footprint. Additionally, this process is suitable for a wide range of operations, from large water treatment plants to small decentralized systems. Recent advances in photocatalytic materials and processes have resulted in higher efficiency and wider applicability. Designing improved photocatalysts with greater light absorption and catalytic performance, merging photocatalysis with

CHAPTER 7

Design of Nanocomposites for Water Treatment

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Abstract: The multifaceted nanocomposites find myriad applications in biomedicine, agriculture, bioimaging, environmental remediation, packaging, and water treatment. Different types of nanocomposites, owing to their high surface area-to-volume ratio, exhibit enhanced porosity, mechanical strength, catalytic activity, conductivity, and optical properties, enabling their wide utilisation to address specific challenges encountered in water purification. This book chapter provides a detailed description of novel nanocomposites employed for water treatment and for improving water quality. The classification of nanocomposites, their composition, synthesis, fabrication methods, structures, and characteristics are discussed in detail. This chapter highlights the application of these advanced functional nanocomposites in ultrafiltration, the removal of dyes and heavy metals, the removal of dissolved gases, and antimicrobial properties for the removal of microbes. The chapter also discusses the advantages, limitations, challenges, future outlook, and environmental impact of these nanocomposites for water treatment and purification.

Keywords: Dyes, Environmental impact, Heavy metals, Nanocomposites, Sustainability, Water treatment.

INTRODUCTION

Water is one of the primary natural resources, instrumental in the sustenance of all forms of life. It is essential to eliminate all harmful microorganisms, as maintaining water quality minimizes their survival and proliferation. However, with rapid urbanisation and industrialisation, water demand has increased exponentially, resulting in water scarcity worldwide. On the other hand, pollution of water bodies remains a global concern due to various sources, including poor sewage treatment, dumping of industrial waste, pollution of seas and oceans, unsecured handling of radioactive materials, and certain farming practices [1, 2]. Pollutants in various wastewater streams mostly include non-biodegradable

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chemical substances. Such contaminants may persist in the food chain for longer periods and pose threats to humans and other organisms within the ecosystem [3, 4, 5]. Consequently, the water quality has deteriorated severely over time. Environmental pollution, especially water pollution, has negative impacts on the economic development and social well-being of various nations. A recent UN report has confirmed that access to freshwater is becoming a key global concern in the 21st century [6, 7]. Many studies have been conducted worldwide to enhance water quality, and these efforts should also be affordable [8, 9].

It is estimated that the world's population will reach 9 billion, leading to increased demand for fresh water and, in turn, the need for wastewater treatment and recycling [1, 2, 6]. The release of untreated wastewater into water bodies would harm the natural environment and affect all of humankind. Therefore, wastewater treatment is of paramount importance. There are four main stages of the basic wastewater treatment systems: preliminary, primary, secondary, and tertiary treatment (Fig. **1**) [10]. The most crucial stage is the preliminary treatment. Coarse particles, such as plastics, that could clog pipes and interfere with the remainder of the procedure are removed in this step. Large particles are filtered through the metal screens, followed by sedimentation of solid materials such as sand, stones, and grit. The other particles are eliminated later by flotation. The primary stage of sewage sludge treatment mainly employs mechanical methods [11, 12]. In this stage, coagulants are used to treat suspended solids, which are then eliminated using clarifiers [13]. Furthermore, secondary treatment is necessary to remove dissolved solids, medications, and microorganisms. This step requires advanced biological treatment techniques, such as sequencing batch reactors, which are systems composed of two tanks [14]. Lastly, the tertiary treatment involves the eradication of microbes, minerals, and scents [15, 16, 17]. All the above methods have been successfully employed for treating water contamination for a very long time, but when utilised on a large scale, they create numerous challenges.

New and complex contaminants are continuously emerging, prompting the development of technologies to address them. However, the ever-expanding efficiency of industrial processes in the last century led to global chemical production reaching 400 million tons in 2000 [12]. It is also noteworthy that from 2000 to 2017, global manufacturing capacity rose from 1.2 billion tons to 2.3 billion tons [13]. The increase in industrial capacity in the 21st century, driven by scientific advancements, has also resulted in unintended consequences, one of which is the increasing occurrence of emerging pollutants from various classes in aquatic systems. Therefore, there is a desperate need for new materials that can help clean up contaminated surroundings.

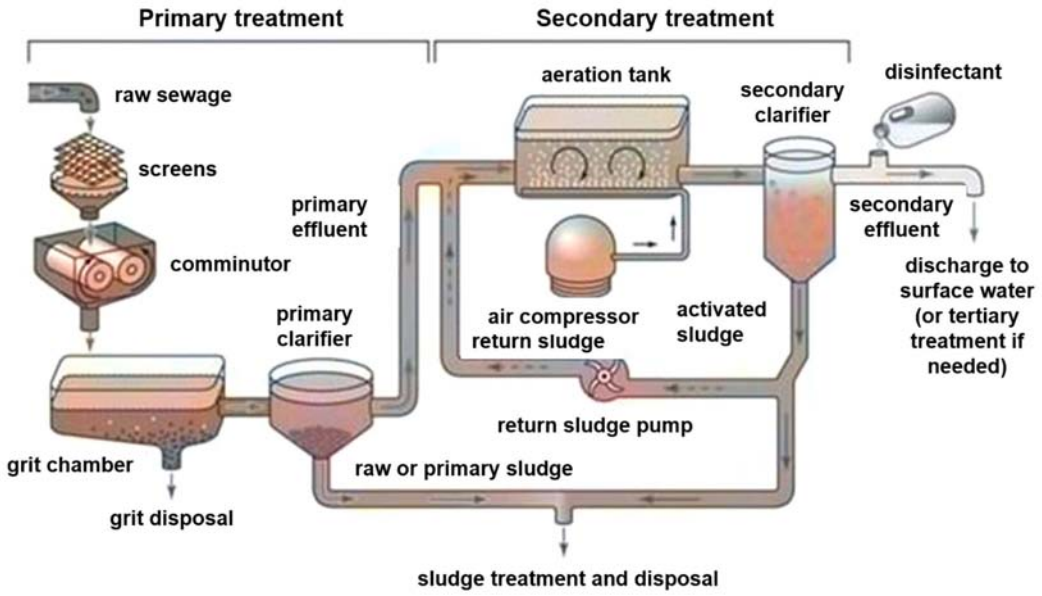


Fig. (1). Schematic illustration of the steps involved in the treatment of wastewater.

In this regard, nanotechnological advances have paved the way for combating water contamination [18]. Nanomaterials can be regarded as a promising and effective approach to addressing severe challenges in advancing effective restorative technologies and safeguarding the environment [19, 20]. Due to high specificity and selectivity, compact size, large surface area, better mechanical stability, reactivity, strong solution mobility, hydrophilic character, hydrophobic character, dispersible character, adsorption properties, catalytic activity, better operating efficiency, and low cost, these nanomaterials offer a revolutionary method for achieving high water quality and acquiring safer water for use across various sectors [21 - 25]. Researchers worldwide are focusing on nanotechnology-based water purification/treatment techniques for effective water disinfection [19, 20]. These processes employ different nanoparticles or other nanomaterials to remove inorganic materials, organic materials, toxic metals, and microbes (Table **1**) [26, 27]. For effluent treatment and enhanced water quality, the size-dependent properties of synthesised nanomaterials proved highly effective [28]. Heavy metals such as Pb, Mo, and others, as well as organic and inorganic pollutants and other harmful microbes, can be removed with high efficiency using various nanomaterials [29 - 31].

CHAPTER 8

Potential Ecotoxicity of Nanomaterials in Water Treatment

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Abstract: Substances with an uncommonly large surface area and high reactivity, with dimensions of 1 to 100 nanometers (nm), are called nanoparticles or nanomaterials (NMs). The overproduction of NMs has raised concerns regarding their ecotoxicological impacts on aquatic and terrestrial ecosystems. Engineered nanomaterials (ENMs) interact with various aquatic organisms, including fish, crustaceans, microalgae, and hydrophytes, often penetrating biological membranes and affecting physiological processes. Silver nanoparticles (AgNPs), titanium dioxide (TiO_2), zinc oxide (ZnO), and carbon-based nanomaterials have been widely studied for their antimicrobial and photocatalytic properties. However, studies on micro-crustaceans such as *Daphnia magna* indicate that exposure to AgNPs can lead to increased mortality, oxidative stress, and developmental abnormalities. In marine bivalves, single-walled carbon nanotubes (SWCNTs) have been found to disrupt neurotransmitter levels, affecting serotonin and dopamine pathways in zebrafish, leading to altered physiological and behavioural responses. Therefore, the primary aim of this book chapter is to explore the potential ecotoxicity of NMs in water treatment, with a focus on their environmental impact and associated risks to living organisms. This book chapter also focuses on the stability and toxicity of NMs in aquatic environments and on bio-inspired green nanomaterials, such as biosorbents and nanobioadsorbents.

Keywords: Biosorbents, Ecotoxicity, Environmental safety, Nanomaterials, Water treatment.

INTRODUCTION

Substances with large surface area and high reactivity, with dimensions of 1 to 100 nanometers (nm), are categorized as nanoparticles or nanomaterials (NMs)

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[1, 2]. In the water treatment process, various technologies, including nanofiltration, nanoadsorbents, nanosensors, nanocatalysts, and magnetic nanoparticles, are used to treat various contaminants in wastewater [3]. It was reported that nanomaterial-based adsorbents are another interesting application in water purification and have attracted significant attention due to their excellent adsorption performance for several organic compounds [4]. It was observed that these materials are particularly effective in wastewater treatment due to their high surface area, strong chemical reactivity, low fouling, high permeability, and low cost. Park *et al*. [5] reported that graphene-based materials have shown exceptional adsorption capacities for removing emerging contaminants from wastewater.

Despite the many advantages of nanoparticles, some toxic effects are also associated. The release of nanoparticles (NPs) into the environment may be influenced by their fate in wastewater treatment processes. Upon reaching wastewater treatment plants (WWTPs), NPs may interact with microorganisms involved in biological treatment systems, reducing their efficiency in treating wastewater [6]. It was reported that engineered nanomaterials (ENMs) interact with aquatic organisms and their ecosystems due to their size. These nanomaterials can easily penetrate biological membranes and therefore reach the physiological systems of most marine animals like fish, algae, and plankton. Brar *et al*. [7] reported that nanoparticles used in cosmetic products were found in wastewater in Sweden and Denmark (50 grams/person/day). Several studies have examined the eco- and genotoxicity of nanoparticles, including Ag, AgO, TiO_2, ZnO, SiO_2, and CuO. These NPs have been shown to interfere with enzyme activity, trigger oxidative stress, and contribute to developmental abnormalities and increased mortality in aquatic organisms [6, 7]. Nanoparticles are also associated with bioaccumulation, meaning the concentration of these nanomaterials in the tissues of living organisms is higher than in the surrounding environment [8]. These impacts lead to harmful effects not just at the species level but also at the ecosystem level. The presence of most organic pollutants is transitory, but nanomaterials may persist in aquatic environments or sedimentary deposits for much longer periods, posing a threat to biological organisms. However, the behaviour of nanomaterials in real ecosystems is relatively little known. Many studies are employing different test species to assess nanotoxicity in terms of lethality, such as oxidative stress, energy reserve alterations, life-history traits, histopathology, biotransformation, and bioaccumulation [9]. Therefore, the toxic effects of nanoparticles on aquatic organisms and ecosystems are important for reducing ecotoxicity. The current book chapter focuses on the potential applications and effects of nanomaterials in living beings, such as fish, algae, hydrophytes, microorganisms, and other aquatic animals, as well as on different uses of NPs.

Source of Nanoparticles in the Environment

Nanoparticle (NP) production has expanded significantly over the past century, with various types of NPs being utilized in fields such as healthcare, environmental science, and consumer products [10]. Understanding the sources, production processes, and environmental implications of NPs is essential for evaluating their impact on both human health and ecosystems. Large-scale manufacturing of titanium dioxide (TiO_2) began in the early 1900s as a safer alternative to toxic white dyes in paints. Over time, the production of TiO_2 has diversified and reached 4 million tons annually. The major applications of TiO_2 include pharmaceuticals, cosmetics, plastics, and the food industry due to its UV-filtering properties, high stability, and non-toxicity [11, 12]. TiO_2 NPs are particularly prominent in sunscreens, where they provide UV protection. Similarly, zinc oxide nanomaterials (ZnO NMs) and silver-based nanomaterials (Ag-NMs) are widely employed across environmental and healthcare applications due to their antimicrobial activity and photocatalytic capabilities [13]. ZnO NMs are commonly found in sunscreens, coatings, food containers, textiles, medical devices, and personal care products. These nanomaterials can enter the environment through wastewater effluents, raising concerns about their potential toxicity to aquatic organisms. It was reported that a notable application of Au-NMs is in laser phototherapy for tumour treatment, where their ability to absorb and convert light into heat plays a crucial role in destroying cancerous cells [14]. The continued advancement of Au-NM technology underscores the need to balance their biomedical benefits with potential environmental and health risks. Therefore, the production and utilization of nanomaterials offer numerous advantages, but their release into the environment is an area of growing concern.

ECOTOXICITY OF NANOMATERIALS

The fate and transport of engineered nanomaterials (ENMs) in aquatic systems are complex processes that can be influenced by numerous environmental parameters (Figs. **1** & **2**). Natural colloids and organic matter play an important role in processes such as aggregation, suspension, and transformation, which are also strongly affected by pH and ionic strength [15]. In freshwater systems, for example, ENMs are known to be more stable than in seawater environments where higher salinities can cause sedimentation within hours to days. Moreover, the release of some ENMs, including silver (Ag) and zinc oxide (ZnO), is an important step in their conversion to potentially harmful ions that could lead to ecological damage [16 - 18]. Therefore, it is essential to understand their behavior in order to reduce the ecotoxicity of nanomaterials. Table **1** and Fig. (**1**) describe the effect of nanoparticles on living beings at different concentrations.

CHAPTER 9

Future Trends in Nanomaterials for Water Treatment: A Patinformatics Analysis

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Abstract: Patinformatics provides crucial insights into the evolution and future trajectory of nanomaterial applications in water treatment. This analysis reviewed approximately 600 patents within the IPC C02F class, uncovering significant trends in technological advancements and potential commercial opportunities. We identified four major future directions: Advanced Nanomaterials (*e.g.*, 2D materials and Quantum Dots), Novel Water Treatment Processes (including Membrane technology and Photocatalysis), Integrated Approaches (combining IoT sensors with renewable energy sources), and improvements in Scalability and Cost-Effectiveness. This study underscores the pivotal role of nanomaterials in advancing sustainable water treatment solutions that align with multiple Sustainable Development Goals (SDGs), particularly SDG 6 on clean water and sanitation.

Keywords: Nanomaterials, Patent landscape, Patentscope, Pollution, Sustainable development goals graphical outline.

INTRODUCTION

The increasing global demand for clean water, coupled with the challenges of water pollution and climate change, has spurred significant advancements in water treatment technologies. Nanotechnology, in particular, has transformed traditional methods by enhancing efficiency, reducing costs, and minimizing environmental impacts. Through the integration of nanomaterials, which offer large surface areas and customizable reactivity, new avenues for sustainable water purification have emerged [1, 2].

This chapter leverages patinformatics to provide a comprehensive overview of the landscape of nanotechnology in water treatment. It explores the patent activity

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related to nanomaterials and their applications, revealing not only current technological capabilities but also pointing towards future innovations (Fig. **1**). Data from major patent databases, such as Patentscope, Scopus, and Google Patents, is analyzed to identify critical trends and potential shifts in this dynamic field.

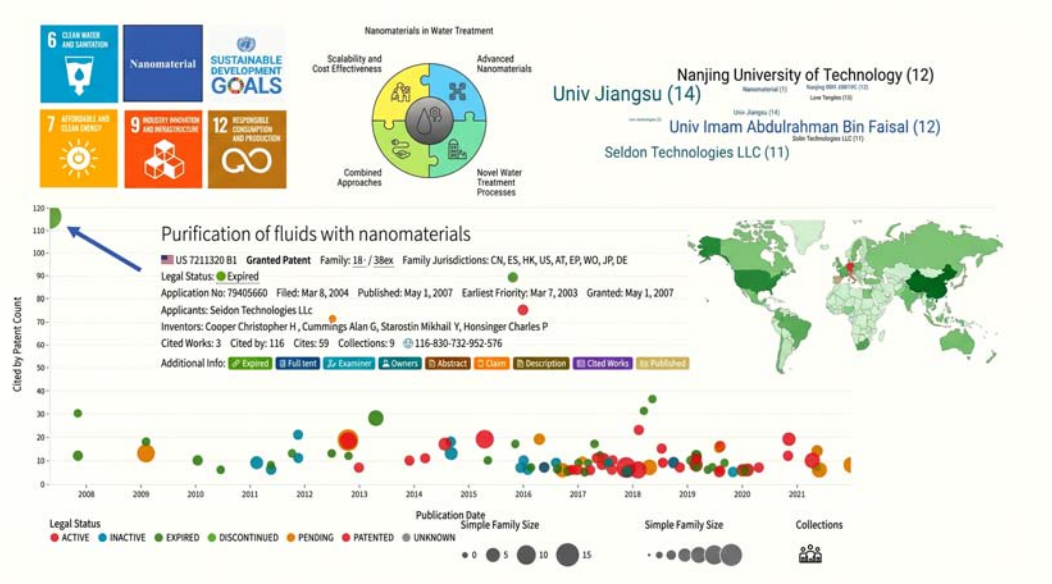


Fig. (1). Overall future trends identified through patinformatics analysis are summarized in the graphical abstract.

Concluding this introduction, our patinformatics analysis aims to bridge the gap between existing technologies and prospective applications, setting the stage for detailed discussions of specific advancements in subsequent sections. This approach will illuminate the pathways through which nanotechnology can continue to contribute to the global pursuit of clean and accessible water.

PATINFORMATICS ANALYSIS TO IDENTIFY FUTURE TRENDS

Patinformatics encompasses the study of patent data, where estimates of technological trends for the sector in question are made, primarily for nanotechnology-based inventions. A great deal of information concerning recent technologies, research gaps, and future potential for commercialization in water treatment can be obtained by studying patent databases. Current analysis enables the prediction of future inventions and supports sound strategic decision-making in research and development. The data collection and filtering that take place focus on patents for advanced nanomaterials used in water treatment. Examples of

applications relevant to this study include adsorption, membrane filtration, and photocatalysis [2, 3]. Recent studies have shown that, in patent filings on the application of nanomaterials for water treatment, the frontrunners are China, the USA, and Iran, reflecting how the overall field is driven cooperatively at the institutional and industrial levels [4]. This trend was observed to be high for patenting technologies related to nanocomposite membranes, metal-oxide photocatalysts, and carbon-based adsorbents such as graphene oxide [1, 3]. There was growth in interest in hybrid systems: the integration of nanomaterials with other techniques, such as electrochemical treatments and the use of renewable sources of energy. One can further observe this trend in the search for a system capable of treating a wide range of contaminants using scalable, cost-effective processes [5, 6]. Besides, newly developed 2D materials, such as graphene and transition metal dichalcogenides, have great potential for both desalination and decontamination owing to their high surface areas, chemical stability, and tunable properties [7]. The analysis also focuses on the sustainability and cost-effectiveness of nanomaterials for large-scale applications [8, 9].

This leads to the implications for future R&D. Clearly, progress in nanomaterial synthesis with minimal nanotoxicity is urgently needed, as this will be pivotal for both regulatory approval and public safety [10]. Furthermore, significant attention must be paid to scalable production methods if lab-scale innovations are to be scaled up into commercial systems [11]. More importantly, advanced integrated patinformatics techniques combined with big data analytics will yield more accurate predictions of technological breakthroughs; the future landscape of water treatment technologies will be relatively well understood [12].

Patent Landscape Analysis: Patent filings and Publication Trends

The patent landscape of nanomaterials in water treatment over the last two decades reflects the dynamic development of innovation in this field and outlines the great potential of nanotechnology for further advancement in this direction. The most striking uptrend began around 2010, and the number of applications soared from 2016 to 2019, reaching a peak of 85 in 2019. This corresponds to the development of advanced nanomaterials, *viz*., 2D materials, quantum dots, and hybrid composites, which have indeed brought about remarkable improvements in water purification through enhanced adsorption, photocatalytic degradation, and antimicrobial properties [2]. This is somewhat reflected in publication trends, with a rapid increase from 2012 to a peak of 93 in 2019. Growth in the number of patents filed, together with the increase in publication output during the period, should therefore indicate an increased emphasis on translating practical, scalable solutions that solve real problems in water treatment [13].

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