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Editorial

Science and Technology for Water Purification: Achievements and Strategies

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1. Introduction

Water scarcity and pollution remain two of the most pressing global challenges, with profound implications for public health, environmental sustainability, and economic development [1,2]. As the global population continues to grow and industrial activities expand, the demand for clean, safe water is steadily increasing [3]. However, water bodies are increasingly polluted by a variety of contaminants, including industrial chemicals [4], agricultural runoff [3,5], pharmaceuticals [4], and microplastics [6]. These pollutants complicate traditional water treatment processes and present significant challenges [7–9], as many emerging contaminants are difficult to remove using conventional filtration and chemical treatments. Consequently, there is a pressing need for more advanced and efficient water purification technologies capable of addressing these evolving issues.

In addition to the growing problem of pollution, many regions are already facing water scarcity, making it crucial to not only focus on wastewater purification but also prioritize its reuse and resource recovery [10]. Traditional purification methods, such as coagulation, filtration, and chemical treatments, often prove inadequate when dealing with the complex nature of modern wastewater [11]. The presence of emerging pollutants such as endocrine disruptors, pharmaceuticals, and novel chemicals further complicates treatment efforts [12]. Therefore, there is an urgent demand for innovative, cost-effective, and sustainable water treatment technologies that can effectively address these new challenges while improving the overall efficiency, sustainability, and affordability of water purification systems [13].

This Special Issue, "Science and Technology for Water Purification", brings together cutting-edge research on the latest advancements in water and wastewater treatment technologies, with a focus on innovative solutions that address the multifaceted challenges of water pollution and scarcity. As global water demand increases and water quality deteriorates due to the discharge of complex pollutants, the research highlighted in this Special Issue offers new perspectives on how to improve existing water treatment processes while creating more sustainable and efficient alternatives. One of the primary goals is to explore innovations aimed at enhancing pollutant removal efficiency, reducing energy consumption, and improving resource recovery from wastewater. The contributions cover a broad spectrum of technological advancements, including the development of novel materials such as advanced adsorbents, catalysts, and nanomaterials that offer superior performance in removing a wide range of contaminants, including heavy metals, pharmaceutical residues, and microplastics. These materials are central to addressing the limitations of conventional treatment methods, which often struggle to effectively remove emerging pollutants. Additionally, this Special Issue features research on innovative reactor designs and hybrid

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treatment systems that can increase the effectiveness and efficiency of wastewater treatment, particularly in high-pollution environments. Another significant focus is the integration of process management strategies and eco-friendly engineering approaches that contribute to sustainable water treatment. These strategies emphasize the need for systems that not only remove contaminants but also recover valuable resources, such as nutrients (e.g., nitrogen and phosphorus) and energy, from wastewater. By incorporating these resource recovery principles, the papers demonstrate how wastewater treatment can evolve from a purely waste management function to a more sustainable, circular process that supports both environmental and economic goals.

2. Review of New Advances

2.1. Reviews on Science and Technology for Water Purification

Two comprehensive review articles are contributed to this Special Issues and survey the latest research and advancements in the field of water and wastewater treatment, providing valuable insights into emerging technologies, trends, and future directions in water purification science. By offering an in-depth analysis of the current state-of-the-art methods, these reviews set the stage for the next wave of innovations in water treatment technologies.

Wang et al. (contribution 1) provide a comprehensive synthesis of research on the removal of contaminants from wastewater using constructed wetland (CW) substrates. The review highlights the role of CW substrates as the primary medium supporting microbial communities, plant roots, and other organisms involved in contaminant removal. It evaluates various substrate types—organic, inorganic, and composite materials—and assesses their effectiveness in treating a wide range of contaminants. Specifically, the following key findings are extracted:

(a) The review categorizes CW substrates, outlining the advantages and limitations of organic, inorganic, and composite materials. Organic substrates, such as compost and peat, provide nutrients for microbes but have limited adsorption capacity. Inorganic materials like sand and gravel offer better physical support and filtration but less microbial activity. Composite substrates, combining organic and inorganic components, enhance both contaminant removal and microbial support.

(b) The primary mechanisms of contaminant removal in CW systems are elucidated, including physical filtration, adsorption, and bioremediation. The combination of physical and biological processes allows CW systems to remove a wide range of pollutants, such as heavy metals, organic compounds, nutrients (nitrogen and phosphorus), and pathogens. Substrate properties, such as porosity and surface area, are shown to influence filtration and adsorption efficiency.

(c) The performance of CW systems in contaminant removal is evaluated, and the effectiveness of different substrates in laboratory and field-scale experiments is compared. The review indicates that selecting and optimizing suitable substrates can lead to high removal efficiencies for various contaminants.

(d) The review addresses challenges, such as substrate clogging, contaminant leaching, and the need for long-term substrate stability under variable conditions. The authors suggest that future research should focus on developing more durable, efficient, and environmentally friendly substrates and optimizing CW system designs to improve performance and reduce maintenance.

(e) The environmental and economic advantages of CW systems for wastewater treatment are emphasized. There is no doubt that wetlands are cost-effective, low-maintenance, and energy-efficient compared to conventional technologies. Multiple ecosystem services are pointed out, such as wildlife habitat, carbon sequestration, and nutrient cycling. The authors advocate broader adoption of CW systems, particularly in small communities, rural areas, and developing countries where conventional treatment infrastructure may be lacking.

Overall, this review provides significant contributions to the field of wastewater treatment by offering a comprehensive analysis of the role of CW substrates in the removal of contaminants. The paper highlights the potential of constructed wetlands as an eco-friendly and cost-effective solution for wastewater treatment, particularly in settings where conventional treatment infrastructure is lacking or unaffordable. By identifying the strengths and limitations of various substrate materials, the review offers valuable guidance for future research and the design of more efficient and sustainable CW systems.

It is known that microplastics have emerged as a significant environmental pollutant and are widely distributed in aquatic ecosystems [6]. Yan et al. (contribution 2) described the interaction between microplastics (MPs) and dissolved organic compounds (DOCs) in water environments. Dissolved organic compounds, including natural and synthetic organic chemicals, are prevalent in water due to industrial, agricultural, and domestic activities. The study focuses on the pathways through which increasing amounts of MPs in water bodies influence the behavior and fate of DOCs and provides insights into the coupled effects of these two types of contaminants on water quality and treatment processes. To be specific, the core findings are as follows:

(a) The study demonstrates that microplastics can adsorb various dissolved organic compounds, particularly hydrophobic DOCs, due to the large surface area and chemical properties of MPs. This interaction leads to changes in the distribution and concentration of DOCs in aquatic environments, potentially altering the behavior and bioavailability of organic pollutants. The authors highlight that MPs serve as a carrier for organic contaminants, thus enhancing their transport and persistence in water systems.

(b) The paper discusses how different characteristics of MPs, such as size, shape, and surface chemistry, influence the adsorption of DOCs. Smaller MPs with larger surface areas show a higher capacity for adsorbing DOCs, while those with functionalized surfaces tend to adsorb specific types of organic compounds more effectively. This finding underscores the complexity of interactions between MPs and DOCs, which can vary depending on the physical and chemical properties of the MPs present.

(c) The study addresses the coupling relationships between MPs and DOCs for aquatic ecosystems and water quality management. The presence of MPs varies the natural cycling of organic matter, potentially leading to the accumulation of harmful organic contaminants in sediments or biota. The adsorption of DOCs on MPs might influence microbial communities in aquatic ecosystems, as the bioavailability of organic compounds can be modified by their association with microplastics.

(d) The interactions between MPs and DOCs that could affect water treatment processes are complex. Traditional water treatment methods may be less effective in removing MPs and the organic contaminants they carry. The review highlights the need for developing more advanced treatment technologies capable of addressing both microplastic pollution and the complex mixtures of organic pollutants that may be adsorbed onto MPs.

(e) The long-term environmental impacts of the coupling between MPs and DOCs should be examined, especially concerning the effects on human health and aquatic life. The kinetics of adsorption, the potential for bioaccumulation of organic pollutants, and the role of MPs in the transport of other contaminants (including heavy metals and persistent organic pollutants) should be further certified.

In conclusion, Yan et al. offer a valuable contribution to our understanding of the complex interactions between microplastics and dissolved organic compounds in water systems. The coupling of these two pollutants has important implications for water quality, environmental health, and water treatment processes. By shedding light on the role of microplastics in the transport and persistence of organic pollutants, this paper underscores the need for more effective pollution management strategies and the development of advanced water treatment technologies capable of addressing both microplastic and organic contamination.

2.2. New Advances in Science and Technology for Water Purification

Crainic and Fechete (contribution 3) compare modern and classic analytical methods for assessing the properties of slaughterhouse wastewater. Given the complex composition of slaughterhouse wastewater, which typically contains high levels of organic matter, fats, oils, and proteins, the study aims to evaluate how traditional (e.g., biochemical oxygen demand (BOD) and chemical oxygen demand (COD)) and modern techniques (e.g., advanced spectroscopic methods and sensor-based technologies) perform in analyzing its composition. The authors highlight the effectiveness of classic methods in determining basic parameters such as pH, suspended solids, and organic load, but emphasize the limitations in providing detailed insights into specific contaminants. In contrast, modern techniques offer more precise, real-time data, enabling a deeper understanding of wastewater characteristics, including the identification of specific pollutants and the variation in composition over time. This paper underscores the value of using both classic and modern methods for assessing slaughterhouse wastewater properties. The integration of these methods enables a more detailed and accurate analysis of complex contaminants, leading to improved treatment strategies. This approach could enhance the efficiency of wastewater treatment processes, particularly in industries like slaughterhouses, where wastewater characteristics are highly variable and challenging to manage.

Bule Možar (contribution 4) investigates the use of advanced oxidation processes (AOPs) as pretreatment for enhancing the biodegradation of polystyrene (PS) and polyvinyl chloride (PVC) microplastics by the fungal species Candida parapsilosis. Microplastics, particularly those made from persistent plastics like PS and PVC, are a growing environmental concern due to their stability and resistance to natural biodegradation. The AOP pretreatment with microbial biodegradation represents an innovative and effective approach to addressing microplastic pollution. This method enhances the biodegradability of otherwise resistant plastics such as PS and PVC, offering a sustainable, eco-friendly solution to plastic waste management. This paper presents a promising strategy for improving the biodegradation of PS and PVC microplastics through AOP pretreatment followed by microbial degradation using Candida parapsilosis. The findings suggest that this combined approach could be a feasible solution for addressing microplastic pollution, particularly in aquatic environments. Furthermore, the effectiveness of certain AOP techniques, such as Fenton, Photo-Fenton, and Fenton-like processes, for the degradation of microplastics including polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) were further evaluated in Bule Možar's report (contribution 5). The AOPs were further investigated in breaking down those persistent plastics, focusing on the comparison of Fenton, Photo-Fenton, and Fenton-like processes. These three techniques show promise for the degradation of PE, PP, and PVC microplastics. Among these, the Photo-Fenton process, enhanced by UV light, was found to be the most effective, particularly for PE and PP. Fenton-like processes, while slightly less efficient, provide a cost-effective alternative using alternative catalysts. The study calls for further research to optimize these methods for practical applications, including reductions in chemical usage, cost, and waste generation in large-scale implementations. Overall, it provides valuable insights into the potential of advanced oxidation processes for addressing microplastic pollution and offers directions for future research in this critical area.

Zhao (contribution 6) addresses a critical environmental issue—the treatment of acid mine drainage (AMD), which often contains high concentrations of toxic metals like iron (Fe) and manganese (Mn). AMD is typically highly acidic due to the oxidation of sulfide minerals in mining operations, leading to the leaching of metal contaminants into nearby water bodies. The research demonstrates that alkaline chemicals, particularly calcium hydroxide (lime), are effective in neutralizing the acidity of AMD. The treatment process successfully raises the pH of the contaminated water, leading to the precipitation of metal hydroxides, such as iron (III) hydroxide and manganese (IV) oxide. This precipitation process reduces the concentrations of dissolved metals and restores the pH to less harmful levels, making the water suitable for discharge or further treatment. The research concludes that alkaline chemical neutralization is an effective and economical method for treating AMD with high concentrations of iron and manganese. By adjusting the pH and precipitating the metals as hydroxides, this method successfully reduces metal toxicity and improves the quality of effluent water.

Chen (contribution 7) reports the use of anaerobic fermentation liquid (AFL) derived from spent mushroom substrates (SMSs) as a carbon source for nitrogen removal in wastewater treatment. Nitrogen contamination, primarily in the form of ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-), is a major environmental concern due to its contribution to eutrophication and the deterioration of water quality. Traditional nitrogen removal methods often involve costly chemicals or energy-intensive processes, making the exploration of alternative, sustainable carbon sources highly valuable. The study demonstrates that AFL from SMSs can be used as an effective carbon source for biological nitrogen removal. The authors reveal that the AFL contains organic compounds, such as volatile fatty acids (VFAs), which can support the growth of microorganisms involved in nitrogen removal processes, such as denitrifying bacteria. The carbon-rich liquid promotes the growth of these microorganisms under anaerobic conditions, leading to efficient nitrogen removal. The AFL promotes the denitrification and ammonification step of microbial nitrogen removal processes, which demonstrates that AFL can serve as a valuable carbon source in wastewater treatment. This paper presents a novel and sustainable approach for nitrogen removal using anaerobic fermentation liquid derived from spent mushroom substrates.

Zhang (contribution 8) investigates the genotoxic effects of silver nanoclusters (AgNCs) on Daphnia magna, a widely used model organism in ecotoxicology. The study reveals that exposure to AgNCs significantly affects the genetic material of *Daphnia magna*, causing genotoxicity. The results show that AgNCs cause DNA damage in *D. magna* as indicated by increased micronuclei formation, which is a marker of chromosomal damage. This suggests that AgNCs, even at relatively low concentrations, can cause genetic alterations that may impact the organism's reproduction and overall population dynamics. A key aspect of the study is the feeding pathway. *Daphnia magna* was exposed to AgNCs indirectly by feeding on aquatic green algae that had absorbed the nanoparticles. This food chain transfer mechanism highlights the potential for nanoparticles to accumulate in lower trophic levels and be passed on to higher organisms. The paper suggests that AgNCs can be absorbed and retained by algae, and can cause genotoxicity upon ingestion by *D. magna*. The findings highlight the need for further research into the environmental and ecological risks of nanomaterials, particularly silver nanoparticles, in freshwater ecosystems. This study underscores the potential for nanoparticles to accumulate and cause genetic damage in aquatic organisms, which could have cascading effects on ecosystem health.

To ensure the safety of oil production systems and protect the underground and surface water environments of oilfields, Zhang (contribution 9) investigated the plugging issues in sand water filter pipes used in crude oil production systems. Sand plugging in filter pipes is a common challenge in oilfields, leading to decreased production efficiency, equipment damage, and increased maintenance costs. The study identifies several key materials involved in the plugging of filter pipes, including sand, crude oil components, water, and precipitates. Sand particles mixed with crude oil and water tend to accumulate and form blockages. These substances interact with water, causing scaling, fouling, and the eventual plugging of the filter system. The integration of different plugging mechanisms—physical clogging, chemical reactions, and biological fouling—into a unified framework is a significant contribution of this paper. These findings can help improve the efficiency of oilfield operations, reduce downtime, lower maintenance costs, and protect the water environment.

3. Conclusions

The two reviews (contributions 1 and 2) emphasize the importance of innovative approaches to water treatment and the need to address emerging contaminants, such as microplastics and their interaction with organic compounds, in efforts to protect aquatic ecosystems and improve wastewater management. Specifically, Wang and colleagues (contribution 1) explore the role of constructed wetlands (CWs) in wastewater treatment, with a particular emphasis on the substrates that support microbial communities and enhance contaminant removal. The review evaluates various types of substrates, such as organic, inorganic, and composite materials, and their efficiency in removing pollutants. The authors discuss the mechanisms involved, including adsorption, filtration, and bioremediation, and suggest ways to improve CW systems for more effective water purification. This approach provides an eco-friendly and cost-effective method for treating wastewater while improving water quality. In contrast, the second study by Yan and colleagues (contribution 2) examines the environmental interaction between microplastics and dissolved organic compounds (DOCs) in aquatic systems. The study investigates how microplastics, as carriers of organic pollutants, affect the distribution and behavior of DOCs, thus altering water chemistry. The authors explore the impact of microplastic contamination on aquatic ecosystems, particularly its potential to transport harmful chemicals and pathogens. This study highlights the complexity of microplastic pollution and its implications for water quality and ecosystem health.

The seven research articles provide distinct contributions to this Special Issue. Specifically, four studies (i.e., contributions 4–7) are focused on chemical (contributions 4, 5 and 6) and biological purification techniques (contribution 7). Those articles showcase a variety of innovative techniques for treating environmental pollutants, from microplastics and nitrogen to heavy metals, emphasizing sustainable and efficient approaches for pollution control and resource recovery in water treatment systems. Specifically, Bule Možar (contributions 4 and 5) explores the use of advanced oxidation processes (AOPs) as a pretreatment method to enhance the biodegradation of PS and PVC microplastics by the fungus *Candida parapsilosis* and compares the effectiveness of Fenton, Photo-Fenton, and Fenton-like processes in degrading PE, PP, and PVC microplastics. The two studies not only demonstrate that AOPs effectively break down microplastic polymers, making them more amenable to microbial degradation, providing a promising approach for mitigating microplastic pollution in aquatic environments, but also find that the Photo-Fenton process, enhanced by UV light, is particularly effective in breaking down these persistent plastics, offering a powerful method for microplastic remediation. Zhao (contribution 6) and Chen (contribution 7) examine the use of alkaline chemical neutralization to treat acid mine drainage (AMD) with high concentrations of iron and manganese, and investigate the use of anaerobic fermentation liquid from spent mushroom substrates (SMSs) as a carbon source for biological nitrogen removal. The two studies provide a sustainable and cost-effective solution for nitrogen-rich wastewater treatment and heavy metal remediation.

The other three studies focus on the monitoring measurements (contribution 3) and eco-environmental damage or security of the water environment (contributions 8 and 9). Specifically, the paper by Crainic and Fechete (contribution 3) underscores the value of using both classic and modern methods for assessing the properties of slaughterhouse wastewater. The integration of these methods enables a more detailed and accurate analysis of complex contaminants, leading to improved treatment strategies. This approach could enhance the efficiency of wastewater treatment processes, particularly in industries like slaughterhouses, where wastewater characteristics are highly variable and challenging to manage. Zhang (contribution 8) indicates that the silver nanocluster leads to significant genotoxic effects. The findings highlight the need for further research into the environmental and ecological risks of nanomaterials, particularly silver nanoparticles, in freshwater ecosystems. The long-term impacts of AgNCs on biodiversity and the potential for bioaccumulation in higher trophic levels should be monitored. Furthermore, the research conducted by Zhang (contribution 9) provides valuable insights into the plugging issues faced by sand water filter pipes in crude oil production systems and offers effective strategies for prevention and mitigation. These findings can help improve the efficiency of oilfield operations, reduce downtime, lower maintenance costs, and protect the water environment.

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