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Emerging trends and future perspectives in adsorption technologies for wastewater treatment: A sunrise or sunset horizon?

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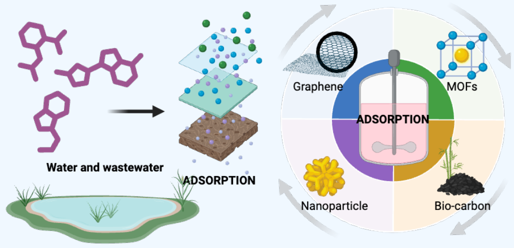
ABSTRACT

Adsorption technology has been a focal point of water and wastewater treatment engineering research for over a century, yielding numerous scientific publications. These studies have primarily concentrated on developing efficient adsorbent materials, understanding adsorption mechanisms and characteristics, and investigating the removal of conventional or emerging pollutants. A common objective cited in most of these reports is the practical application of the adsorption process in municipal water or wastewater treatment plants, aiming to enhance water quality and safety. However, the majority of these studies overlook issues related to technology transfer, thereby widening the gap between academic recommendations and their practical implementation in industry. In this review, we trace the evolution of adsorption technology in water and wastewater treatment, evaluating its application viability and highlighting the approaches that hold the greatest promise for the future. Furthermore, we propose strategies for scientists and engineers dedicated to advancing research efforts that translate into industrially viable adsorption technologies for water treatment. While the practical effectiveness of adsorption technologies may not fully align with academic enthusiasm, this critical evaluation should not dismiss their potential as future technology since adsorption retains significant and distinct advantages that merit further exploration.



Keywords: *Adsorption; Wastewater Treatment; Water Treatment; Adsorbent*

1. INTRODUCTION

Adsorption technology has undergone significant evolution in water and wastewater treatment, benefiting from over a century of extensive research [1, 2]. At its core, adsorption involves the accumulation of ions, atoms, or molecules on the surface of a solid material, referred to as the adsorbent [3]. Typically, this phenomenon is propelled by the adsorbent's surface energy, arising from an unbalanced attractive force on its surface. Adsorption is categorized into two types, chemical and physical, based on the nature of the attraction between the adsorbate molecule and the adsorbent surface. Physical adsorption, characterized by its reversibility and exothermic nature, involves weak electrostatic and van der Waals forces. In contrast, chemical adsorption is an endothermic and irreversible process, occurring through the formation of chemical bonding between the adsorbate and the adsorbent [3].

The adsorption technique, a longstanding and widely adopted method in water treatment and environmental remediation, benefits from using readily available adsorbents such as natural materials, industrial by-products, and agricultural residues. Adsorption's role in water treatment has a rich history, originating in ancient times when charcoal, sand, and gravel were used to purify drinking water. In the late 19th and 20th centuries, it became a key method for removing color, taste, and odor from water, significantly reducing the risk of waterborne diseases such as cholera and typhoid. More recently, the method has adapted to contemporary challenges, targeting the removal of emerging contaminants like pharmaceuticals, personal care products, hormones, and endocrine disruptors from water sources contaminated by human and animal wastes.

While adsorption technology offers considerable benefits, it encounters distinct challenges that impede its transition from academic research to industrial application [4, 5, 6]. These challenges include selecting and designing suitable adsorbents for various pollutants and water matrices, necessitating a nuanced understanding of adsorbent-pollutant interactions [7]. Integrating adsorption with other treatment methods, such as biological treatments, oxidation, and membrane processes, requires careful optimization to ensure efficiency and compatibility [8, 9]. Furthermore, the regeneration and reuse of spent adsorbents and managing adsorption residues are critical for environmental sustainability and economic viability [10, 11]. Additionally, the scale-up and practical implementation of the adsorption systems in real-world scenarios demands a comprehensive approach considering technical, economic, and environmental factors [4].

Global researchers are actively advancing adsorption technology in water and wastewater treatment, tackling the aforementioned challenges [12, 13]. This enthusiasm is mirrored in

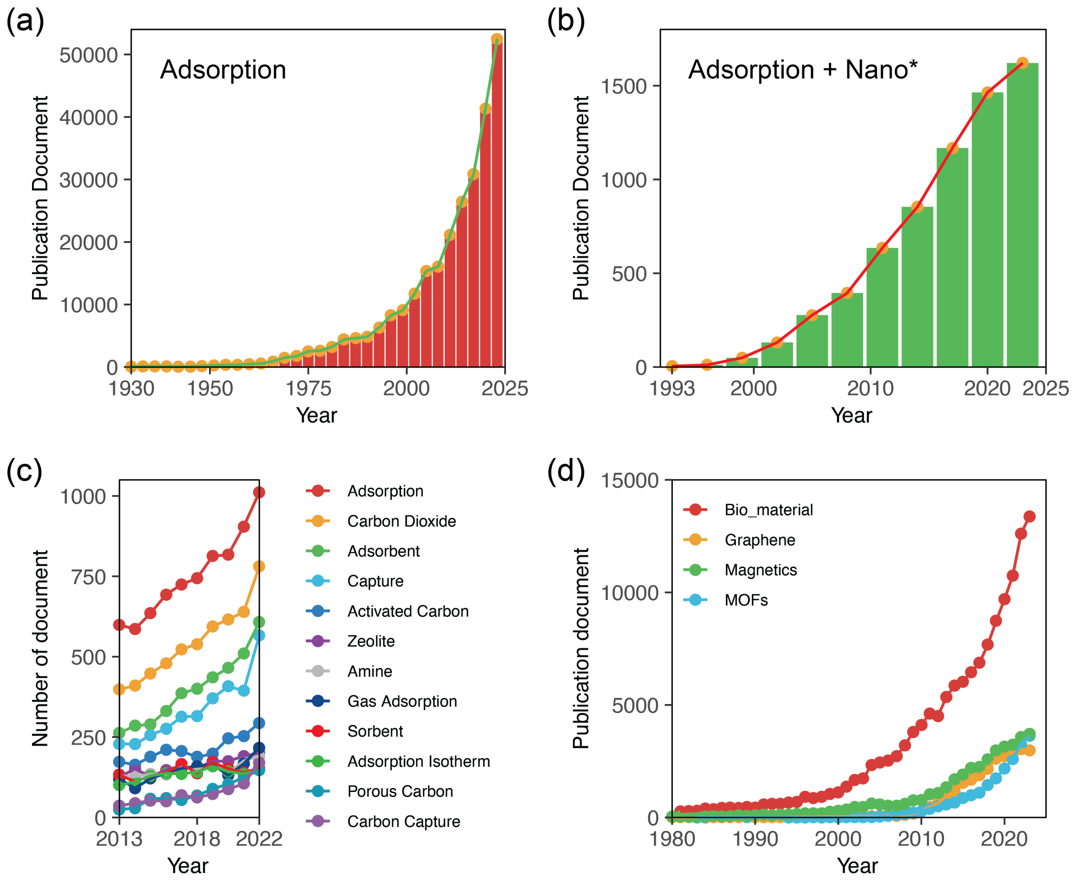


Figure 1. (a) Trends in the number of publications on adsorption technology in the Scopus database; (b) Recent advancements (2013–2022) in adsorption research within Topic Cluster 772 (Adsorption), according to SciVal analysis

the scientific community, as evidenced by a notable increase in publications on adsorption technology, with over 50,000 articles published in 2022 alone (Figure 1). This surge underscores the field's growing research interest [14]. However, a closer examination reveals a significant focus on the fundamental aspects of adsorption, with many studies overlooking its implementation in real-world wastewater treatment systems [15, 16]. Given these trends, it is crucial for the research community to reassess the trajectory of adsorption technology in water treatment to enhance its applicability in real-world scenarios and narrow the gap between academic advocacy and industrial application.

In this study, we aim to critically evaluate the current state of adsorption technology in water and wastewater treatment. We focused on identifying the barriers to technology transfer, assessing the practical feasibility of novel adsorbents, and pinpointing essential research directions to overcome these challenges. Through this comprehensive analysis, we seek to address the pivotal question of how to bridge the gap between academic advancements and real-world applications in adsorption technology.

2. RECENT TRENDS IN ADSORPTION TECHNOLOGY

Adsorption processes have played a central role in water treatment for many years. This technology has been used for wastewater treatment since the early 1990s when it was first applied to remove color and odor from water [1]. Since then, adsorption has been developed and improved to treat various types of contaminants, like heavy metals, dyes, pesticides, pharmaceuticals, and personal care products [7, 17, 18]. Among various water treatment technologies, adsorption remains the most effective method for removing pollutants from wastewater. It offers advantages such as low cost, simple operation, and straightforward design [19].

Figure 2(a) depicts the upward trend in adsorption technology development, showcasing research outputs from Scopus indexed publications. The data reveals a consistent annual increase in publication from its inception in 1930 to 2023, culminating in over 50,000 publications in the last year alone. The significant surge in publication began in 2000 and has persisted to the present year. Several factors contributed to the rapid advancement in adsorption research during this period, including technological breakthroughs in research, rising demand, emerging applications, and enhanced funding and collaboration efforts [20]. For instance, the advent of nanotechnology in the late 20th century revolutionized material design at atomic and molecular levels, leading to novel adsorbents with enhanced properties and greater surface areas [21]. As depicted in Figure 1(b), the trend in the research employing nanomaterial in adsorption research has also increased significantly over the period of 2000 – 2023. Concurrently, the emergence of sophisticated characterization techniques, such as atomic force microscopy and advanced spectroscopy, offered deeper insight into the adsorbent's structures and functions, facilitating their optimization [22]. Furthermore, growing environmental awareness and the pressing need for sustainable technologies fueled interest in leveraging adsorption for water purification, wastewater treatment, and the removal of hazardous pollutants [23].

An in-depth analysis of the adsorption key phrase, using SciVal data from 2013 to 2022, as shown in Figure 1(c), reveals an expansion in the field's applications, extending beyond water treatment to include gas adsorption, especially carbon dioxide. This expansion was driven by growing concerns over climate change and the implementation of stricter greenhouse gas emission regulations, prompting the search for effective CO2 capture solutions [24]. Adsorption emerged as a promising option, especially for point-source capture at industrial sites such as power plants and refineries [25].

As mentioned earlier, adsorption is still an active area of research and development, as new adsorbents, mechanisms, models, and applications are being explored and evaluated. Over recent decades, there has been a significant surge in developing innovative adsorbent materials for water and wastewater treatment (see Figure 2) [26]. These novel materials are engineered with specific properties – such as increased surface area, enhanced porosity, and tailored functional groups – to enable the highly efficient capture of targeted contaminants [27]. For instance, metal-organic frameworks (MOFs), known for their exceptional porosity and customizable features, provide unmatched surface areas and adjustable functionalities for selective adsorption [28]. Similarly, graphene-based materials stand out for their superior adsorption capacities and regeneration potential, making them high-performance options [29]. Additionally, magnetic nanoparticles have gained attention for their ease of separation from treated water thanks to their magnetic properties, which facilitate straightforward regeneration and reuse [30]. Furthermore, bio-based adsorbents derived from agriculture waste, biomass, or algae present sustainable and cost-effective alternatives, contributing to the field's diversity and innovation [31, 32]. The summary of the developed novel materials and the targeted pollutants, their adsorption performance, and their application technique is presented in Table 1.

Recently, research in the field has extended beyond developing new adsorbent materials, with some studies focusing on integrating adsorption with complementary techniques to boost treatment efficiency and performance [8, 9]. This interdisciplinary approach combines adsorption with methods like membrane separation, advanced oxidation processes, electrochemical treatments, and biological processes, aiming for synergistic effects surpassing each standalone technique's limitations [33]. For example, membrane separation can efficiently separate adsorbents from treated water, while advanced oxidation processes can degrade adsorbed contaminants [34]. Similarly, electrochemical treatments offer potential pathways for adsorbent regeneration, and biological processes enable the biodegradation of adsorbed pollutants, illustrating the multifaceted benefits of these integrated treatment strategies. In their recent research, Sayed et al. explored an integrated treatment approach combining biological degradation by medicinal mushrooms, ultraviolet irradiation, and adsorption using bentonite and dolomite. This innovative method was applied to both synthetic and real wastewater, achieving complete removal of sulfamethoxazole, diclofenac, and estrone and substantially reducing acetaminophen and citalopram levels [35].

In conclusion, adsorption is a versatile and efficient technique for removing many contaminants from water, including dyes, heavy metals, organic compounds, and pharmaceuticals. Its advantages include high selectivity, broad applicability, and low energy requirements. Despite these benefits, the technology faces hurdles such as the costliness of adsorbent materials, the necessity for effective adsorbent regeneration and recovery, the management of spent adsorbents, and the challenges involved in system scale-up and optimization [20]. Several improvements are necessary to address these challenges and facilitate the industrial application of adsorption technology. Firstly, there is a need to develop novel adsorbents from sustainable and cost-effective materials, including biomass, waste products, and nanomaterials, to enhance both environmental and economic viability. Additionally, integrating adsorption with complementary techniques—such as membrane filtration, advanced oxidation processes, electrochemical treatments, and biological processes—can enhance overall treatment efficiency, broaden the range of treatable contaminants, and improve system scalability and sustainability.

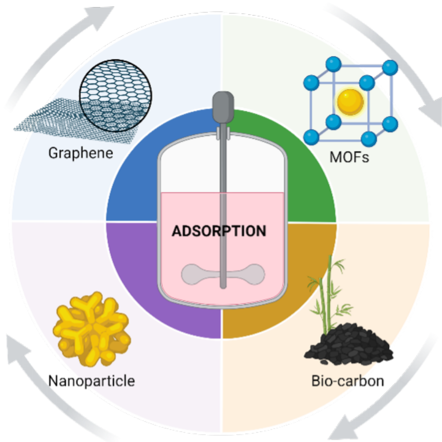


Figure 2. Novel materials developed as adsorbent in water and wastewater treatment

3. ADSORPTION TECHNOLOGY KEY-FACTOR

The previous section highlighted the increasing focus on advancing adsorption technology for water and wastewater treatment within the last decades. This section will delve into the essential factors for successfully deploying these technologies in real-world applications. Key aspects to be discussed include material selection and design, process optimization, system integration, regeneration and reusability, and economic viability.

3.1 Material selection and design

The selection and design of adsorbent materials are pivotal for the successful application of adsorption in water treatment, directly influencing the adsorption process and reactor configurations. An ideal adsorbent for industrial water treatment should be cost-effective and widely available, as this accounts for a significant portion of operational expenses, approximately 70% [36]. It is crucial that these materials can be procured and transported to treatment facilities in large quantities without logistical challenges [36]. Furthermore, adsorbents must exhibit chemical stability to perform consistently across various water matrices with differing pH levels, conductivity, and ionic strengths [17]. Mechanical robustness is also essential, particularly for continuous column-based operations, to prevent high-pressure drops and maintain process efficiency. High adsorption capacity is another critical attribute, reducing the volume of adsorbent required and thereby enhancing cost-efficiency [37]. Moreover, the chosen adsorbent should adhere to stringent water quality standards set by regulatory bodies to ensure the treated water meets the necessary safety criteria. Lastly, the ability to regenerate and reuse the adsorbent material multiple times is a key consideration, offering substantial reductions in operational costs and contributing to the overall sustainability of the water treatment process [38].

Identifying and developing a material encompassing all the characteristics presents a significant challenge in real-world scenarios. As highlighted in the previous section, several classes of novel materials have emerged, demonstrating considerable potential in water treatment. Among these, bio-carbon-based materials, such as biochar and activated carbon, stand out for their widespread application and effectiveness in contaminant removal [22, 39]. Additionally, metal-organic frameworks (MOFs), with their highly porous structures and customizable functionalities, have gained attention for their selective adsorption capabilities [40]. Graphene-based materials are also notable for their exceptional adsorption capacities and potential for easy regeneration [41]. Furthermore, magnetic nanoparticles offer a unique advantage in water treatment processes due to their ease of separation, facilitated by their magnetic properties [30]. Each of these material classes brings distinct advantages to water treatment applications, reflecting the diverse and innovative approaches being explored to meet the stringent demands of adsorption technology.

In conclusion, various materials have demonstrated their suitability for real-world water treatment applications, meeting some standard criteria for adsorbent materials. Notably, bio-carbon-based materials, metal-organic frameworks (MOF), graphene-based materials, and magnetic nanoparticles each offer unique advantages that contribute to the effectiveness of adsorption processes. However, despite these advancements, the quest for the ideal adsorbent—with optimal cost-effectiveness, stability, capacity, and sustainability—remains ongoing. The continuous development and innovation of new adsorbent materials are imperative to achieve all the desired characteristics, ultimately leading to more efficient and sustainable water treatment solutions.

3.2 Adsorption Reactor Selection

In the realm of adsorption for water treatment, the operation mode is a critical factor that dictates the process's efficiency and applicability [42]. The discontinuous batch adsorption process, prevalent in academic research, involves mixing a predetermined quantity of adsorbent with a pollutant-containing solution until equilibrium is achieved [43]. This method is lauded for its flexibility, simplicity, and cost effectiveness, making it particularly suitable for laboratory studies and small-scale applications [43]. However, its scalability to larger operations is limited, often resulting in variability in treatment efficiency and a more labor-intensive separation process after each batch.

On the other hand, the column fixed-bed adsorption technique, although less frequently documented in the literature, is the cornerstone of large-scale water treatment operations [44]. This continuous process, where contaminated water flows through a column packed with adsorbent material, offers the advantages of consistent treatment efficiency, suitability for automation, and the capacity to handle large volumes of water [45]. Despite these benefits, challenges such as adsorbent saturation, system design and maintenance complexity, and higher initial costs present hurdles to its broader adoption. Each adsorption technique, with its distinct advantages and drawbacks, plays a pivotal role in the context of its application, influencing the choice between batch and continuous operations based on specific treatment requirements and scale.

3.3 The adsorption regeneration

Regeneration of adsorbents is a critical aspect of adsorption technology, pivotal for ensuring the economic feasibility and environmental sustainability of the process [46]. The ability to recover and reuse adsorbent materials not only diminishes operational costs but also aligns with eco-friendly practices by minimizing waste generation [47]. However, the regeneration process is complex and highly dependent on the nature of the adsorption mechanism involved. Physical adsorption, characterized by weaker van der Waals forces, generally allows for more straightforward regeneration, often achievable through simple desorption methods such as temperature increase or pressure reduction [48]. These methods can effectively release adsorbed molecules from the adsorbent surface without significantly compromising the material's structural integrity or adsorption capacity.

In contrast, chemical adsorption involves stronger covalent bonds between adsorbate and adsorbent, making regeneration more challenging [47]. Regeneration in such cases may require more intensive treatments, such as chemical reactions, thermal treatment at higher temperatures, or even solvent extraction, to break the bonds and rejuvenate the adsorbent. These processes can be more energy-intensive and may potentially degrade the adsorbent material over multiple regeneration cycles, affecting its longevity and efficiency. Moreover, the choice of regeneration method is influenced by various factors, including the type of adsorbate, the adsorbent material, and the specific application requirements [49]. Effective regeneration strategies must be carefully designed to balance the need for efficient adsorbate removal with the preservation of adsorbent properties and environmental considerations.

Given these complexities, ongoing research and development in the field of adsorbent regeneration are vital. Innovations aimed at improving the efficiency, cost effectiveness, and sustainability of regeneration processes can significantly enhance the overall viability of adsorption technology in water and wastewater treatment. Exploring new materials with inherent regenerative capabilities or developing hybrid techniques that combine the strengths of different regeneration methods could provide promising pathways forward.

4. THE FUTURE DIRECTION OF ADSORPTION TECHNOLOGY

As outlined in the preceding discussions, the large-scale application of adsorption technology in water and wastewater treatment necessitates a comprehensive approach that extends beyond the fundamental aspects such as adsorbent types, operational modes, and regeneration processes. It is imperative to also focus on the technology transfer aspects to bridge the gap between laboratory research and practical applications. By adopting this holistic perspective, we can more effectively address the challenges associated with implementing adsorption technology in the field of water and wastewater treatment in the near future [50].

We posit that future research should intensively address the existing limitations of adsorption technology, with a particular emphasis on the development of advanced adsorbent materials, the integration of hybrid and sophisticated adsorption systems, and the optimization of processes. Equally important are efforts to align adsorption practices with sustainability and circular economy principles, enhance the regeneration and reusability of adsorbents, and overcome challenges related to the commercialization and scaling of these technologies. Addressing these focal areas will be pivotal in unlocking the full potential of adsorption technology in water and wastewater treatment [51].

4.1 Advanced Adsorbent Materials

Focusing on the development of advanced adsorbent materials represents a crucial frontier in enhancing the efficacy and scope of adsorption technology in water and wastewater treatment. This endeavor involves not only the synthesis of new materials but also the innovative modification of existing ones to achieve unprecedented levels of efficiency, specificity, and environmental compatibility. The quest for advanced adsorbent materials involves synthesizing novel compounds that offer superior adsorption capacities, selectivity for specific contaminants, and improved kinetics. This includes exploring new classes of materials such as metal-organic frameworks (MOFs), covalent organic frameworks (COFs), and nanomaterials, each offering unique porous structures and surface chemistries tailored for specific adsorption applications [10].

Enhancing the performance of adsorbents also involves the strategic modification of material surfaces to introduce functional groups that are specifically attractive to target pollutants [52]. Such modifications improve the adsorption capacity and enhance the selectivity of adsorbents, enabling the efficient removal of specific contaminants from complex wastewater matrices. With an increasing emphasis on sustainability, there is a growing trend towards developing adsorbents from renewable or waste resources [47]. Bio-based adsorbents, such as biochar and modified agricultural by-products, are gaining attention for their cost effectiveness and reduced environmental footprint. These materials not only contribute to waste valorization but also align with the principles of the circular economy.

The development of hybrid adsorbents, which combine multiple materials or adsorptive mechanisms, presents a promising approach to overcoming the limitations of single-component systems [53]. Such composite materials can offer synergistic effects, resulting in enhanced adsorption properties, improved mechanical strength, and increased resistance to fouling. Research is also advancing towards the creation of 'smart' adsorbents that can respond to environmental stimuli, such as pH, temperature, or the presence of specific contaminants. These materials can offer dynamic adsorption capabilities, allowing for more controlled and efficient contaminant removal under varying operational conditions [30].

4.2 Hybrid and Advanced Adsorption Systems

The integration of hybrid and advanced adsorption systems represents a strategic evolution in water and wastewater treatment technologies, aiming to amplify the efficiency, scope, and flexibility of traditional adsorption processes [13]. This approach leverages the synergistic potential of combining adsorption with other complementary treatment methods, thereby enhancing overall performance and addressing a broader range of contaminants. Combination with Membrane Technologies: Integrating adsorption processes with membrane filtration, such as reverse osmosis or ultrafiltration, offers a powerful treatment solution [41]. This hybrid system can effectively remove a wide array of contaminants, from large particulates and colloids to dissolved organic and inorganic compounds. The adsorption process can reduce the membrane fouling potential by pre-treating the water, thus extending membrane life and reducing maintenance costs.

Coupling adsorption with AOPs, such as ozonation, UV irradiation, or Fenton reactions, can lead to the enhanced degradation of persistent organic pollutants [34]. The adsorption component concentrates the contaminants, making them more susceptible to oxidative degradation, while AOPs can regenerate the adsorbent surface in situ, enhancing the cyclic use of adsorbents. The incorporation of electrochemical processes with adsorption technologies provides a dual mechanism for contaminant removal and adsorbent regeneration. Electro-absorption, for example, utilizes electrically charged surfaces to enhance adsorption efficiency, while electrochemical regeneration can desorb adsorbed pollutants, restoring the adsorbent's capacity [8]. Combining adsorption with biological processes, such as activated sludge or biofiltration, enables the comprehensive treatment of both biodegradable and non-biodegradable pollutants. Adsorption can remove recalcitrant compounds that are resistant to biological degradation, while biological treatment can degrade organic matter, reducing the load on the adsorption system.

The development of advanced control systems and process optimization algorithms is essential for the efficient operation of hybrid adsorption systems. Real-time monitoring and adaptive control strategies can dynamically adjust process parameters in response to fluctuating water quality conditions, ensuring optimal performance and resource utilization [50]. Exploring innovative reactor designs and system configurations, such as moving bed adsorption systems, sequential batch reactors with integrated adsorption stages, or fluidized bed adsorbers, can offer enhanced contact efficiency, operational flexibility, and scalability.

4.3 Regeneration and Reusability

The regeneration and reusability of adsorbents are key factors in adsorption technology's sustainability and economic viability in water and wastewater treatment. Effective regeneration strategies extend the life cycle of adsorbent materials and reduce waste generation and operational costs, making the adsorption process more environmentally friendly and cost-effective [49]. Developing efficient and gentle regeneration methods is crucial for maintaining materials' integrity and adsorptive capacity over multiple cycles. Techniques such as thermal desorption, chemical elution, ultrasonic cleaning, and supercritical fluid extraction are explored for their effectiveness in regenerating various adsorbents [49]. The choice of technique often depends on the adsorbent material, the type of adsorbate, and the specific adsorption mechanism involved.

One of the challenges in adsorbent regeneration is the energy requirement, particularly for thermal processes. Innovations in low-energy regeneration methods, such as microwave-assisted regeneration or the use of waste heat sources, are being investigated to minimize the energy footprint of the regeneration process [47]. Moreover, the long-term stability of adsorbents under repeated regeneration cycles is a critical concern. Research focuses on the development of robust adsorbent materials that can withstand structural and chemical changes over numerous regeneration cycles without significant loss of adsorption capacity or selectivity [11]. Implementing closed-loop systems where regenerated adsorbents are continuously reused within the treatment process can significantly enhance the sustainability of adsorption technologies. Such systems require careful monitoring and management to ensure consistent treatment performance and to prevent the accumulation of secondary pollutants.

The management of spent adsorbents and regeneration by-products is an integral aspect of the adsorption process. Strategies for waste minimization, such as the recovery of valuable compounds from spent adsorbents or the conversion of spent materials into useful products (e.g., construction materials, soil amendments), contribute to the circular economy and reduce the environmental impact of the adsorption process [54]. The safe handling and disposal of regenerated adsorbents and any hazardous by-products are subject to regulatory guidelines. Compliance with environmental regulations and the implementation of best practices for waste management are essential for the responsible operation of adsorption-based treatment systems.

5. CONCLUSION

In concluding this comprehensive review of adsorption technology in water and wastewater treatment, we reflect on the significant strides made in understanding and enhancing this versatile treatment method. The exploration of advanced adsorbent materials, coupled with innovative hybrid and advanced adsorption systems, has broadened the scope of contaminants that can be effectively removed from water sources. The challenges associated with the regeneration and reusability of adsorbents have spurred research into novel regeneration techniques and materials designed for longevity and minimal environmental impact. These efforts are crucial for reducing operational costs and fostering the sustainable application of adsorption technology on a larger scale. As we look to the future, the continuous development of new materials, the integration of adsorption with other treatment processes, and the refinement of regeneration methods will be pivotal in addressing water and wastewater treatment's complex and dynamic challenges. The potential for adsorption technology to contribute to global water purification efforts is vast, with ongoing research and innovation key to unlocking this potential.

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AUTHOR CONTRIBUTIONS

TT: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing, Visualization, Funding acquisition. **AR:** Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Funding acquisition.

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