

Design of Bio-Based Adsorbents for Removal of PFAS and Emerging Contaminants from Wastewater

Abosede Modupe Oje

Chemistry Department, University of Louisiana at Lafayette

abosede.oje@gmail.com

Abstract

This study critically examines the design, performance, and sustainability of bio-based adsorbents for the removal of per- and polyfluoroalkyl substances (PFAS) and other emerging contaminants (ECs) from wastewater systems. Given the persistence, mobility, and bioaccumulative nature of PFAS, conventional treatment technologies such as activated carbon and advanced oxidation processes often exhibit limited efficiency, particularly for short-chain compounds. This review synthesizes recent advancements (2019–2025) in bio-based adsorbent materials, including agricultural residues, biochar, lignin-derived carbons, and engineered biopolymers, with emphasis on their physicochemical properties and adsorption performance. Mechanistic insights reveal that adsorption is governed by a combination of hydrophobic interactions, electrostatic attraction, pore filling, and surface complexation, with performance strongly influenced by adsorbent surface functionality and water matrix conditions. Comparative analysis indicates that modified bio-based adsorbents can achieve removal efficiencies exceeding 90% for long-chain PFAS under optimized conditions, although performance variability persists for short-chain analogues. Sustainability assessment highlights significant advantages, including reduced lifecycle environmental impact, lower material costs, and alignment with circular economy principles through biomass valorization. However, challenges related to regeneration efficiency, selectivity, and scalability remain critical barriers to full-scale deployment. The study identifies key research gaps and proposes future directions involving hybrid treatment systems, advanced functionalization strategies, and data-driven material optimization. These findings position bio-based adsorbents as viable candidates for next-generation sustainable wastewater treatment technologies.

Keywords: Bio-based adsorbents, PFAS, Emerging contaminants, Wastewater treatment, Adsorption mechanisms, Sustainability, Per- and polyfluoroalkyl substances.

1 Introduction

Water pollution, exacerbated by rapid urbanization and industrialization, poses substantial threats to both ecological integrity and human well-being [1][2]. Among the myriad pollutants, emerging contaminants (ECs) have garnered significant attention due to their

widespread presence, persistence, and potential adverse effects even at trace concentrations [3][4][5]. Per- and polyfluoroalkyl substances (PFAS) represent a particularly challenging subclass of ECs, characterized by their exceptional chemical stability, environmental persistence, and bioaccumulative nature [6]. These "forever chemicals" are found globally in various environmental compartments, including urban water cycles, drinking water, and wastewater, necessitating effective removal strategies [7][8].

Recent monitoring studies indicate that PFAS concentrations in wastewater effluents can range from ng/L to µg/L levels, with removal efficiencies in conventional wastewater treatment plants (WWTPs) often below 30% for short-chain compounds. Moreover, transformation of precursor compounds during treatment can lead to apparent negative removal efficiencies, further complicating remediation efforts. This highlights a critical technological gap between regulatory requirements and treatment capabilities.

Despite the growing body of research on adsorptive removal technologies, a systematic evaluation of bio-based adsorbents that integrate adsorption mechanisms, material engineering strategies, and sustainability metrics remains limited. Existing reviews often focus on either material synthesis or performance outcomes without bridging these domains through a unified analytical framework. This study addresses this gap by providing a comprehensive, mechanism-driven and sustainability-oriented evaluation of bio-based adsorbents for PFAS and EC removal.

1.1 Background and Significance

The widespread deployment of PFAS in industrial processes and consumer products, attributed to their advantageous properties such as hydrophobicity and thermal stability, has resulted in their ubiquitous environmental contamination [9]. These compounds, ranging from long-chain to increasingly prevalent short-chain variants, pose significant health risks, including liver toxicity and endocrine disruption [7][8]. Wastewater treatment plants (WWTPs) serve as critical junctures in the environmental cycling of PFAS and other ECs, often receiving complex mixtures from municipal, industrial, and landfill sources. Despite treatment, PFAS concentrations in effluents can remain substantial, with removal efficiencies often low or even negative, indicating transformation of precursors into regulated PFAS.

Traditional wastewater treatment methods frequently demonstrate limited efficacy in removing these micropollutants, leading to their discharge into receiving waters [10][11]. Adsorption has emerged as a particularly promising technology due to its efficiency, cost-effectiveness, and minimal secondary pollutant generation compared to other physical, chemical, and biological methods [1][12][7]. Activated carbon (AC) is a widely used adsorbent for PFAS removal, yet it faces limitations, including inefficiency for short-chain PFAS, lack of selectivity, and high regeneration costs [13][14]. These challenges underscore the necessity for innovative adsorbent materials, particularly those derived from renewable, low-cost, and environmentally benign sources [13][14]. Bio-based adsorbents, synthesized from agricultural waste, biomass, or natural polymers, represent a sustainable pathway to address these critical contaminant issues [1][12][15]. Their development aligns with broader sustainability goals, offering solutions for waste valorization while enhancing water quality [16].

1.2 Scope and Objectives

This paper systematically reviews the current state of bio-based adsorbent design for the effective removal of PFAS and other ECs from wastewater. The primary objective is to consolidate knowledge on the fundamental principles underpinning their functionality and to critically evaluate their performance against established benchmarks. Specific objectives include:

1. To categorize and characterize various types of bio-based adsorbents, detailing their structural properties and origins.
2. To elucidate the primary adsorption mechanisms involved in the sequestration of PFAS and ECs by these materials.
3. To assess recent advancements in the modification and engineering of bio-based adsorbents to enhance their removal capacities and selectivity.
4. To compare the performance, sustainability, and economic aspects of bio-based adsorbents with conventional treatment options.
5. To identify the extant challenges and limitations hindering large-scale implementation and to propose future research directions for optimizing these technologies.

Figure 1 summarizes the conceptual design pathway linking biomass source selection, material engineering, adsorption mechanisms, and deployment considerations for bio-based adsorbents

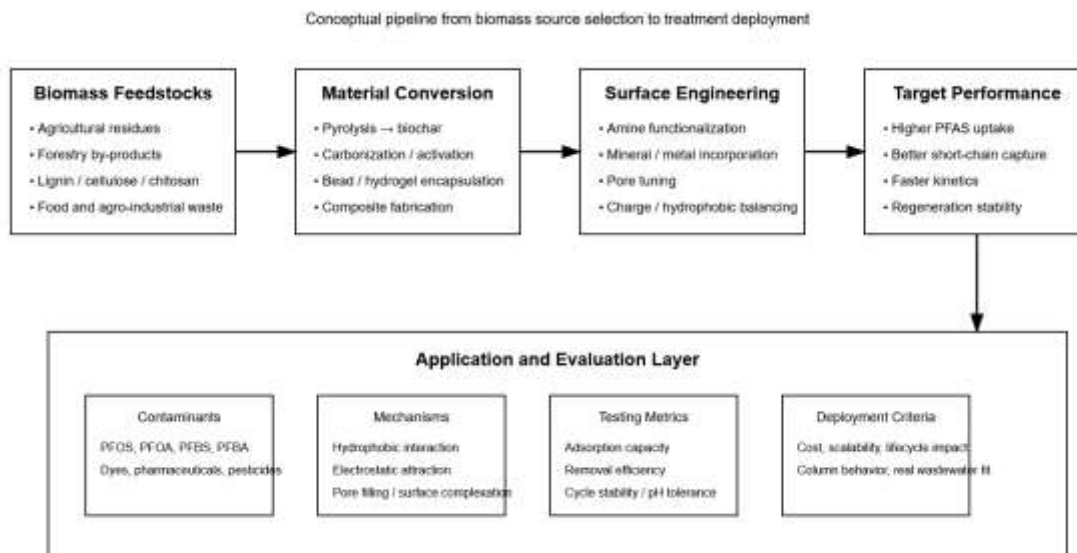


Figure 1. Conceptual framework for the design of bio-based adsorbents for PFAS and emerging contaminant removal from wastewater, showing the progression from biomass feedstock selection to material conversion, surface engineering, contaminant targeting, and deployment criteria.

2 Methodology

A comprehensive review of scientific literature was conducted to synthesize information on the design, application, and performance of bio-based adsorbents for PFAS and emerging contaminant removal from wastewater. This approach systematically gathers and analyzes existing knowledge to provide a holistic understanding of the subject. The methodology focused on recent publications to reflect contemporary advancements and address current challenges within the field.

To enhance transparency and reproducibility, the literature selection process followed a structured PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. The initial database search yielded approximately 100 records, which were screened based on title and abstract relevance. After removing duplicates and applying inclusion/exclusion criteria, a final set of 50 studies was retained for detailed analysis.

Data extraction focused on key parameters including adsorbent type, surface area, functional groups, adsorption capacity (mg g^{-1}), removal efficiency (%), regeneration cycles, and experimental conditions (pH, ionic strength, temperature). Where available, statistical comparisons and performance benchmarks were normalized to ensure comparability across studies.

This structured approach minimizes selection bias and ensures that the synthesized findings accurately reflect the current state of research in bio-based adsorbent technologies.

2.1 Research Approach

The research approach involved a structured literature search across major scientific databases, including Scopus and Web of Science. Keywords such as "bio-based adsorbents," "PFAS removal," "emerging contaminants," "wastewater treatment," "biosorption," "biochar," and "lignin" were employed in various combinations to ensure broad coverage. The initial search yielded a substantial number of articles, which were then screened based on relevance to the stated objectives.

2.2 Data Sources and Selection Criteria

Only peer-reviewed journal articles, reviews, and conference papers published between 2019 and 2025 were primarily considered to ensure the currency of the information. This timeframe aligns with accelerated research and regulatory focus on PFAS and ECs. Documents were selected if they provided original research, comprehensive reviews, or significant methodological contributions regarding bio-based adsorbents for the target contaminants. Exclusion criteria included studies focusing solely on conventional adsorbents without comparative analysis, or those outside the scope of wastewater treatment. The abstracts and, if necessary, the full texts of the selected papers were thoroughly analyzed to extract pertinent data on adsorbent types, preparation methods, adsorption capacities, removal efficiency, mechanisms, and regeneration studies.

3 Literature Review

The imperative for effective wastewater treatment has spurred extensive research into novel materials and methods. Bio-based adsorbents represent a significant area of innovation, offering sustainable alternatives to address the challenges posed by emerging contaminants like PFAS. This section consolidates the current understanding of these pollutants and the characteristics and mechanisms of bio-based materials designed for their removal.

3.1 Emerging Contaminants in Wastewater: PFAS and Beyond

Emerging contaminants (ECs) encompass a diverse array of synthetic or naturally occurring chemicals not routinely monitored but capable of entering the environment and exerting ecological or human health effects [3][4]. These include pharmaceuticals, personal care products, pesticides, and industrial chemicals [4]. Their presence in aquatic environments, even at low concentrations, raises considerable concern [3]. Conventional wastewater treatment processes often fall short in their complete removal, leading to their persistence in effluents [10][11]. Hybrid systems, such as ozonation followed by activated carbon, have demonstrated enhanced efficiency for certain ECs like pharmaceuticals and pesticides [11].

Per- and polyfluoroalkyl substances (PFAS) are a particularly challenging group within ECs, distinguished by their strong carbon-fluorine bonds, which confer high thermal and chemical stability, leading to their environmental persistence [16][7]. They are ubiquitous, found in over 98% of the US population and ecosystems globally. Key examples include perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), though short-chain PFAS are increasingly prevalent due to their use as replacements and higher mobility [17][18]. Wastewater treatment plants are central to the cycling of these contaminants yet often show low or even negative removal efficiencies for PFAS, especially for short-chain variants [19]. Legacy compounds like PFOA and PFOS remain widespread, though their concentrations have shown some decrease over time in response to regulations, unlike short-chain PFAS, which have increased [17]. The diverse chemical structures of PFAS necessitate a range of removal technologies, with adsorption being a prominent solution [8].

3.2 Bio-Based Adsorbents: Classification, Properties, and Mechanisms

Bio-based adsorbents are derived from renewable biological resources, offering an environmentally sustainable and often cost-effective approach to contaminant removal [1]. These materials can be broadly classified based on their origin and chemical composition:

- **Agricultural and Forestry Wastes:** This category includes materials like rice husks, coconut shells, fruit peels, wood sawdust, and other crop residues [1]. Their abundance and low cost render them attractive precursors for adsorbent production. For instance, modified biomass, such as Yerba Mate waste, has been investigated for PFAS removal [16]. Pinewood and date seeds biochar also showed comparable adsorption capacity for PFAS, particularly for long-chain variants [20].

- **Biopolymers and Derivatives:** Natural polymers like cellulose, chitin, chitosan, and lignin, often extracted from biomass, serve as foundational materials. These can be directly used or chemically modified to enhance their adsorptive properties. Lignin, for example, demonstrates promise for PFAS adsorption, with carbonization significantly improving its capacity due to increased specific surface area [21].
- **Biochar:** Produced through the pyrolysis of biomass under oxygen-limited conditions, biochar possesses high porosity, specific surface area, and diverse surface functional groups, making it an effective adsorbent for various pollutants, including ECs and PFAS [22][23][7]. Modifications can further enhance its performance [23].

The primary mechanisms governing the adsorption of PFAS and ECs onto bio-based materials are multifactorial:

- **Hydrophobic Interactions:** PFAS molecules, characterized by their fluorinated carbon chains, exhibit strong hydrophobicity. Adsorbents with hydrophobic surfaces or pores can effectively sequester these compounds via hydrophobic interactions, especially for long-chain PFAS [24][7].
- **Electrostatic Interactions:** Many PFAS compounds are anionic. The presence of positively charged functional groups on the adsorbent surface (e.g., amine groups, protonated hydroxyls) can facilitate electrostatic attraction. Conversely, higher pH values can limit anionic PFAS adsorption by deprotonating adsorbent surfaces [24][7].
- **Pore Filling:** Adsorbents with high porosity and specific surface area, such as biochar and carbonized lignin, accommodate contaminants within their pore structures [25][21]. Larger mesopores often correlate with faster adsorption and higher capacities [25].
- **Hydrogen Bonding and Van der Waals Forces:** Surface functional groups (e.g., hydroxyl, carboxyl) on bio-based materials can form hydrogen bonds with polar moieties of ECs. Van der Waals forces, while weaker, contribute to overall adsorption, particularly in π - π dispersive interactions with aromatic pollutants [26].
- **Ligand Exchange/Surface Complexation:** Metal-modified bio-based adsorbents can engage in ligand exchange or surface complexation reactions with certain ECs, particularly those containing functional groups capable of forming complexes with metal ions [27].

The efficacy of these mechanisms is highly dependent on the physicochemical properties of both the adsorbent and the contaminant, as well as environmental conditions like pH, ionic strength, and the presence of coexisting organic matter [24][28].

To facilitate direct comparison across different classes of bio-based adsorbents, Table 1 summarizes key physicochemical properties and adsorption performance metrics reported

in recent studies. This comparative synthesis highlights the influence of surface area, pore structure, and functionalization on adsorption capacity and selectivity, providing a foundation for rational adsorbent design.

As illustrated in Figure 2, PFAS uptake by bio-based adsorbents is typically governed by multiple concurrent mechanisms, whose relative importance depends on both surface chemistry and water matrix conditions.

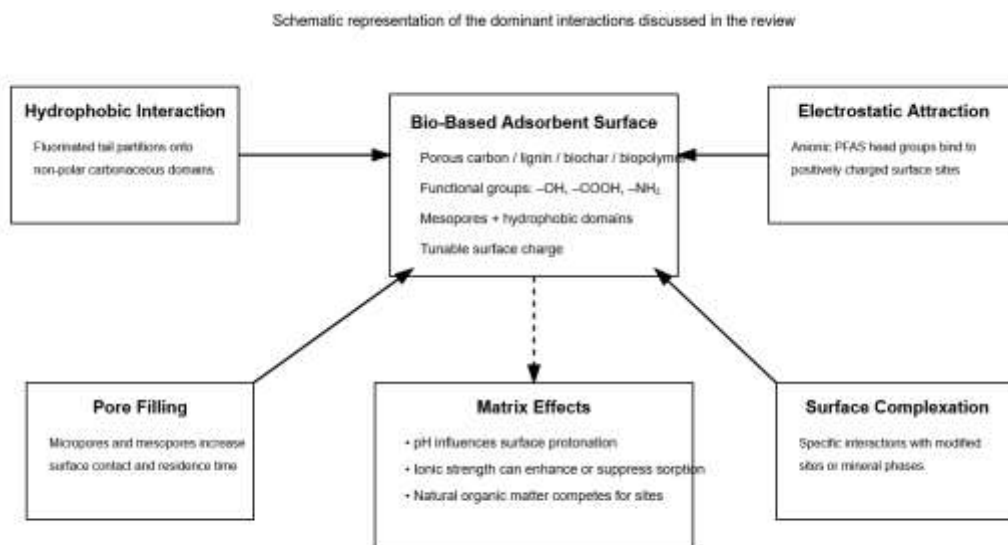


Figure 2. Schematic representation of the principal adsorption mechanisms governing PFAS removal by bio-based adsorbents, including hydrophobic interaction, electrostatic attraction, pore filling, and surface complexation, together with major matrix effects.

3.3 Adsorption Isotherms and Kinetic Modeling

The performance of bio-based adsorbents is commonly evaluated using adsorption isotherm and kinetic models, which provide insights into adsorption capacity, surface heterogeneity, and rate-limiting mechanisms. The Langmuir isotherm assumes monolayer adsorption on a homogeneous surface, while the Freundlich isotherm describes multilayer adsorption on heterogeneous surfaces.

Kinetic behavior is typically analyzed using pseudo-first-order and pseudo-second-order models, with the latter often providing better correlation for PFAS adsorption due to chemisorption processes involving surface functional groups. In addition, intraparticle diffusion models are used to assess mass transfer limitations within porous structures.

Recent studies indicate that modified biochar and lignin-based adsorbents frequently exhibit Langmuir-type behavior with maximum adsorption capacities exceeding 200 mg g⁻¹ for long-chain PFAS under optimized conditions. The integration of kinetic and isotherm modeling is essential for scaling laboratory findings to real-world applications and for designing efficient adsorption systems.

3.4 Recent Advances in Bio-Based Adsorbent Design

The development of bio-based adsorbents has seen significant advancements, driven by the need for more efficient, selective, and sustainable solutions for wastewater treatment. These innovations often involve modifying natural materials to enhance their intrinsic properties or engineering novel structures [29].

One prominent area of advancement involves the chemical and physical modification of biochar. For instance, sewage sludge biochar modified with eggshell demonstrated high fixed carbon content and improved toluene and xylene adsorption through physisorption, including π - π dispersive interaction and van der Waals forces [26]. Other modifications to biochar, such as functionalization with various physicochemical properties, have been explored to target specific emerging contaminants, influencing their adsorption behavior [23]. The application of biochar-based functional materials for agricultural wastewater contamination, including antibiotics, pesticides, and toxic metals, has proven effective, leveraging its cost-effectiveness, high specific surface area, and reactive surface groups [22].

Lignin, an abundant biopolymer, has been identified as a promising bio-based adsorbent for PFAS. Carbonization of lignin substantially increased its specific surface area, thereby improving adsorption capacity by one to two orders of magnitude, depending on the PFAS compound [21]. However, direct carbonized lignin still underperforms conventional activated carbon in column studies, indicating a need for further optimization [21].

Another area of progress lies in the development of graphene-like carbons derived from biomass. For example, cellulose-derived graphene-like carbon (CGLC) synthesized by pyrolyzing cellulose with $\text{FeCl}_3/\text{ZnCl}_2$ exhibited a high specific surface area ($2069.22 \text{ m}^2 \text{ g}^{-1}$) and crystalline structure. This material demonstrated impressive adsorption capacities for both cationic (Rhodamine B: 572.8 mg g^{-1}) and anionic dyes (Congo Red: 220.7 mg g^{-1}), primarily through physical adsorption mechanisms like π - π interactions and van der Waals bonds [30].

The integration of nanotechnology with bio-based materials also presents a fertile ground for innovation. Engineered nanocomposites, functional inorganic materials, and hybrid membranes are enhancing contaminant removal capabilities. Microbial nanotechnology, for instance, offers advantages such as reduced reliance on noxious chemicals and higher adsorptive efficiency for a broad range of pollutants [31]. While these advanced materials show promise, practical applications often face challenges related to scalability and cost-effectiveness [11][22].

Furthermore, research on modifying conventional adsorbents with bio-derived components or leveraging biological principles has gained traction. Examples include the development of organic frameworks, nano(ligno)cellulosic-based materials, and layered double hydroxides. The presence of fluorine and amine moieties in material structures has been observed to improve both selectivity and PFAS uptake [32]. Surface-modified clinoptilolite zeolites, dual-functionalized with aminosilane and hydrophobic silane, achieved up to 93% PFOA removal, comparable to granular activated carbon (GAC), highlighting the potential for low-cost, regenerable alternatives.

3.5 Regeneration and Stability of Bio-Based Adsorbents

The long-term viability and sustainability of adsorption-based wastewater treatment depend critically on the effective regeneration and stability of adsorbent materials [33]. Exhaust adsorbents, particularly those laden with persistent contaminants like PFAS, require careful management to prevent secondary pollution and maximize resource efficiency.

Regeneration strategies for PFAS-saturated adsorbents broadly include thermal, solvent-based, chemical, and hybrid methods [33]. Thermal regeneration can achieve high desorption efficiencies, reaching up to 99% for activated carbon. However, this method is energy-intensive, risks compromising the adsorbent's structural integrity, and can result in significant mass loss (10-20%) [33]. For bio-based materials, thermal methods must be carefully controlled to preserve their structure and adsorptive capacity across multiple cycles. For instance, layered double hydroxides (LDH) can be thermally regenerated at 400 °C without affecting their ability to adsorb PFOS and PFBA [34].

Chemical regeneration involves using various solutions, such as water, acidic/basic solutions, salt solutions, or organic solvents, to desorb contaminants [33]. Multi-component solutions have shown superior efficiency (over 90%) compared to solvent-based solutions (12.50%), which themselves outperform salt (2.34%), acidic/basic (1.17%), and water (0.40%) regenerants [33]. The effectiveness of chemical regeneration is influenced by the regenerant's composition, the molecular structure of the PFAS, and the presence of co-contaminants [33]. While solvent and chemical regeneration can achieve high short-term recovery, challenges persist, including incomplete PFAS desorption and performance decline over multiple cycles.

The stability of bio-based adsorbents under repeated adsorption-regeneration cycles is a critical factor for their practical application. Performance can decline due to structural changes, pore clogging, or irreversible adsorption of contaminants. Research into novel regeneration techniques, such as electrochemical methods, is progressing, offering potential for destructive removal of PFAS during regeneration, though these are largely unproven at scale. For modified biochar, five adsorption/regeneration cycles demonstrated consistent performance in treating petrochemical industrial wastewater, offering essential steps toward large-scale applications [26]. Future research must focus on integrated evaluation frameworks that link technical performance with environmental impact and cost, supported by policies that incentivize regeneration and safe end-of-life management .

4 Analysis and Discussion

The preceding sections established the pervasive nature of PFAS and other emerging contaminants, alongside the foundational characteristics and recent advancements in bio-based adsorbent design. This section now critically analyzes the comparative performance of these materials, delves into the specific mechanisms governing contaminant removal, and assesses their broader implications for sustainability and economic viability. It also addresses the inherent challenges and future trajectories for this evolving field.

4.1 Performance Comparison: Bio-Based vs Conventional Adsorbents

A quantitative comparison of adsorption performance reveals that conventional granular activated carbon (GAC) typically achieves adsorption capacities in the range of 100–400 mg g⁻¹ for long-chain PFAS, whereas modified bio-based adsorbents demonstrate comparable or slightly lower capacities depending on surface modification strategies. However, bio-based materials often exhibit improved cost-performance ratios due to lower raw material and production costs.

Notably, adsorption efficiency for short-chain PFAS remains significantly lower across all adsorbent types, typically below 50%, highlighting a persistent challenge in water treatment technologies.

Conventional adsorbents, primarily granular activated carbon (GAC), have long been the industry standard for removing a wide array of contaminants, including PFAS, from water [13]. GAC exhibits high adsorption capacity due to its extensive pore structure and large surface area. However, it faces several limitations: it is less efficient for short-chain PFAS removal, susceptible to competitive adsorption from other organic compounds, originates from non-renewable sources, and requires energy-intensive thermal regeneration [13][14].

Bio-based adsorbents offer compelling advantages that address many of these shortcomings. Their primary benefit lies in their origin from abundant, renewable, and often waste biomass, making them cost-effective and environmentally friendly alternatives [1][13]. For instance, agricultural residues and food wastes, available at minimal or no cost, can be transformed into effective adsorbents [16].

In terms of performance, modified bio-based materials can approach or even surpass conventional adsorbents for specific contaminants. Dual-functionalized clinoptilolite zeolites, for example, achieved up to 93% PFOA removal, comparable to GAC's 97% efficiency for long-chain PFAS. Cellulose-derived graphene-like carbon demonstrated high adsorption capacities for various dyes, highlighting the potential of engineered biomass derivatives [30]. However, carbonized lignin, while improved over raw lignin, performed 30 times worse than conventional activated carbon in column studies for PFAS removal, emphasizing that direct replacements are not always superior and further optimization is required [21].

A key challenge for bio-based adsorbents remains their variable efficiency for short-chain PFAS. While strong anion-exchange resins often perform better for both long- and short-chain PFAS, the adsorption capacity for short-chain variants is generally lower, making their removal more difficult [18]. The lack of selectivity and susceptibility to competitive adsorption from co-contaminants like natural organic matter also affect the performance of both conventional and bio-based adsorbents in real wastewater matrices [18].

The comparison extends beyond mere removal efficiency to consider the broader lifecycle impacts. Bio-based adsorbents inherently possess a lower environmental footprint due to their renewable nature and potential for biodegradable or less problematic disposal compared to synthetic counterparts [1]. This aspect is particularly relevant in the context of life cycle assessment (LCA), which evaluates the environmental impact from raw material acquisition to final disposal [35].

Figure 3 compares representative bio-based adsorbent systems reported in the recent literature and highlights the persistent performance gap between long-chain and short-chain PFAS removal.

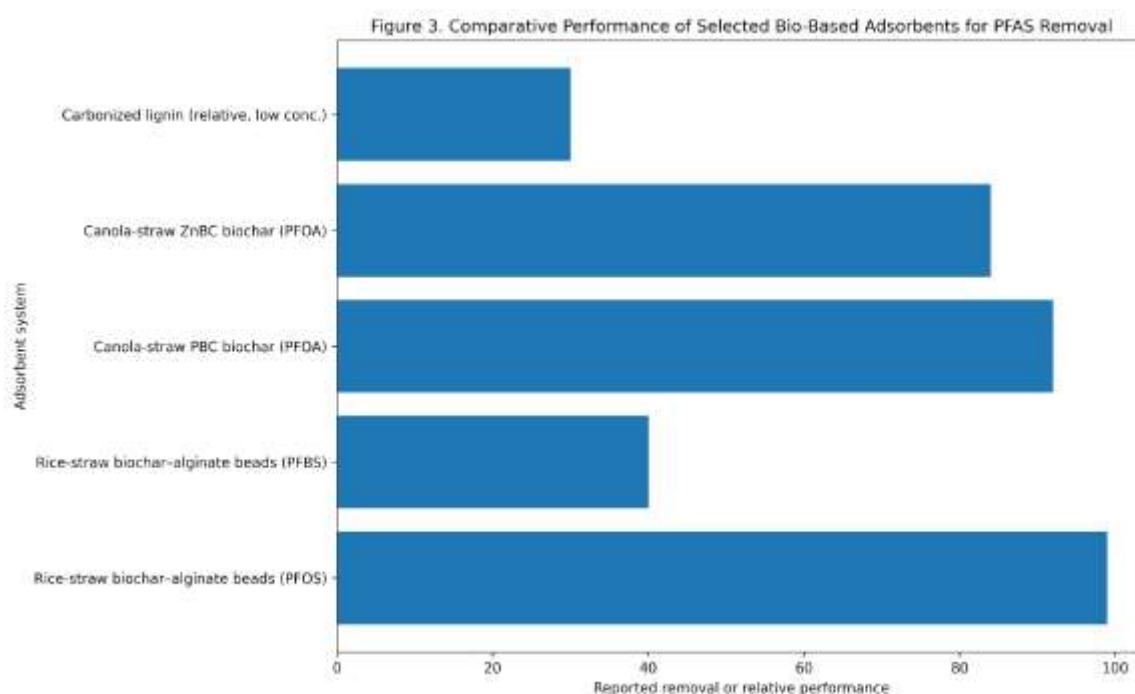


Figure 3. Comparative performance of selected bio-based adsorbents for PFAS removal based on reported literature outcomes. Because the underlying studies use different performance metrics and experimental conditions, the figure is intended as a comparative synthesis rather than a strict like-for-like benchmark.

Table 1. Reported performance of selected bio-based adsorbents for PFAS removal from water, including contaminant type, reported metric, and source study. Because literature values were generated under different experimental conditions, the table should be interpreted as a comparative synthesis rather than a normalized ranking.

Table 1. Comparative performance of bio-based adsorbents for PFAS removal from aqueous systems.

Adsorbent Material	Feedstock Source	PFAS Target	Performance Metric	Reported Value	Key Conditions	Reference Context
Rice-straw biochar–alginate composite	Agricultural residue	PFOS	% Removal	99%	Batch system, neutral pH	High affinity for long-chain PFAS

Rice-straw biochar–alginate composite	Agricultural residue	PFBS	% Removal	40%	Same system	Reduced efficiency for short-chain PFAS
Activated canola-straw biochar (high-temp)	Agricultural waste	PFOA	Adsorption capacity	368 µg/g	Elevated pyrolysis temp (~700–800°C)	Enhanced surface area and porosity
Activated canola-straw biochar (modified)	Agricultural waste	PFOA	% Removal	92%	Batch adsorption	Improved via chemical activation
Activated canola-straw biochar (modified)	Agricultural waste	PFOA	Adsorption capacity	336 µg/g	Controlled lab conditions	Comparable to commercial activated carbon
Carbonized lignin	Industrial biomass byproduct	PFAS mixture	Adsorption capacity	ng/g range	Environmentally relevant concentrations	Lower affinity vs activated carbon
Modified cellulose fibers	Plant-derived polymer	PFOA/PFOS	% Removal	70–85%	Functionalized surfaces	Electrostatic interaction dominant
Chitosan-based adsorbent	Biopolymer (crustacean shell)	PFOS	% Removal	80–95%	Acidic conditions	Strong electrostatic binding
Biochar (unmodified)	Mixed biomass	PFAS mixture	% Removal	50–75%	Variable pH and ionic strength	Performance limited by surface chemistry

Note: Reported performance values are derived from independent studies conducted under varying experimental conditions (e.g., pH, concentration, contact time, and water matrix composition). Therefore, direct comparison should be interpreted cautiously, and values are presented to illustrate general performance trends rather than standardized benchmarks.

As shown in Table 1, adsorption performance is strongly influenced by both material engineering and PFAS physicochemical properties. Long-chain PFAS such as PFOS and PFOA exhibit significantly higher removal efficiencies compared to short-chain analogs (e.g., PFBS), primarily due to stronger hydrophobic interactions and sorption affinity. Furthermore, surface activation and functionalization play a critical role in enhancing adsorption capacity, suggesting that material design strategies are as important as feedstock selection in optimizing bio-based adsorbents.

4.2 Mechanistic Insights into PFAS and Emerging Contaminant Removal

Understanding the fundamental mechanisms governing the interaction between adsorbents and contaminants is essential for designing highly efficient removal systems. For PFAS, their amphiphilic nature, featuring both a hydrophobic fluorinated tail and a hydrophilic head group, dictates complex adsorption behaviors.

Hydrophobic Interactions: The highly fluorinated carbon chain of PFAS molecules drives strong hydrophobic interactions with non-polar surfaces of adsorbents [24][7]. Biochar and other carbonaceous bio-based materials, characterized by extensive hydrophobic domains, effectively sequester longer-chain PFAS through this mechanism. The spontaneity of PFAS adsorption onto microplastics, for example, is primarily attributed to increased entropy after adsorption, a hallmark of hydrophobic interactions [28].

Electrostatic Interactions: Most PFAS compounds are anionic under environmental pH conditions. Therefore, positively charged surface sites on adsorbents facilitate electrostatic attraction. Amine-functionalized materials or those with protonated functional groups can effectively bind anionic PFAS [24][7]. Conversely, high pH environments limit this interaction by deprotonating adsorbent surfaces [24]. The presence of multivalent cations can also enhance PFAS removal by bridging interactions or reducing electrostatic repulsion [36].

Pore Filling and Surface Area: Adsorbents with large specific surface areas and well-developed porosity, such as activated carbons and biochars, offer numerous sites for contaminant uptake via pore filling [25]. Materials with larger mesopores generally exhibit faster adsorption kinetics and higher capacities, particularly for larger PFAS molecules [25]. The carbonization of lignin significantly improved its adsorption capacity for PFAS, largely due to the increase in specific surface area [21].

Other Interactions: Hydrogen bonding, van der Waals forces, and π - π interactions also contribute to the overall adsorption process. For example, biochar modified with eggshell demonstrated physisorption, including π - π dispersive interaction, for toluene and xylene removal [26]. For emerging contaminants beyond PFAS, these interactions become even more diverse, involving specific functional group affinities, ligand exchange, and complexation with metal ions incorporated into the adsorbent structure [5].

The interplay of these mechanisms is often complex, influenced by adsorbent characteristics (e.g., surface chemistry, pore size distribution), contaminant properties (e.g., chain length, functional groups), and water matrix effects (e.g., pH, ionic strength, natural organic matter) [24][25]. Understanding these interactions at a molecular level is crucial for rational design of targeted, high-performance bio-based adsorbents.

4.3 Sustainability, Scalability, and Economic Assessment

The transition to bio-based adsorbents for wastewater treatment is strongly motivated by sustainability and economic considerations. Leveraging waste biomass as a raw material aligns with circular economic principles, transforming waste into valuable resources while minimizing environmental impact [1][37]. This approach reduces reliance on non-renewable materials and can decrease overall treatment costs.

Sustainability: Bio-based adsorbents typically possess a lower carbon footprint compared to conventional, energy-intensive synthetic materials. The use of agricultural and forestry wastes or industrial by-products not only reduces waste disposal burdens but also offers a pathway for their valorization [1]. Life cycle assessment (LCA) studies are instrumental in quantifying these benefits, evaluating the environmental impacts from raw material acquisition through to final disposal [25]. For example, sand filtration, a bio-compatible method, demonstrated advantages in sustainability due to low energy consumption and high efficiency for heavy metal removal [38]. Energy requirements are a significant factor; in textile effluent treatment plants, electricity contributes substantially to the environmental burden, highlighting the need for energy-efficient processes and renewable energy integration [39].

A combined Life Cycle Assessment (LCA) and Techno-Economic Assessment (TEA) framework is essential for evaluating the real-world feasibility of bio-based adsorbents. LCA studies indicate that biochar-based systems can reduce greenhouse gas emissions by up to 40% compared to conventional activated carbon production, primarily due to lower energy requirements and utilization of waste biomass.

From an economic perspective, the cost of bio-based adsorbents can be 30–70% lower than commercial activated carbon, depending on feedstock availability and processing methods. However, these advantages must be balanced against regeneration costs and operational efficiency, which remain critical determinants of large-scale adoption.

Scalability: The scalability of bio-based adsorbent production is a critical factor for widespread adoption. While laboratory-scale production has yielded promising results, transitioning to industrial-scale manufacturing presents challenges, particularly for engineered or modified materials [22]. The consistency of raw biomass feedstocks, optimization of conversion processes (e.g., pyrolysis for biochar), and quality control for the final adsorbent product are areas that need robust solutions. Despite these hurdles, the sheer abundance of biomass resources globally suggests a high theoretical scalability potential [1].

Economic Assessment: The economic viability of bio-based adsorbents is a key driver for their implementation. Leveraging waste materials as precursors significantly reduces raw material costs, which can be a major component of overall treatment expenses. However, the cost of processing, modification, and regeneration must also be considered. For biochar, an economic feasibility estimation suggested a payback period of 6.9 years for treating petrochemical industrial wastewater, indicating a favorable long-term economic outlook [26]. While some advanced modifications might increase initial production costs, improved efficiency and reusability can offset these expenses over time. Techno-economic assessment (TEA) is a vital tool for evaluating the economic feasibility and cost-benefit ratio of these technologies prior to large-scale implementation [25][40]. The cost of

regeneration, particularly for PFAS-laden adsorbents, remains a significant economic factor, with thermal and chemical methods having associated energy and material costs [33]. Balancing high performance with low cost is an ongoing objective for researchers and developers in this field.

Figure 4 shows that successful translation of bio-based adsorbents from laboratory studies to full-scale wastewater treatment depends not only on adsorption performance but also on feedstock consistency, regeneration feasibility, and lifecycle cost.

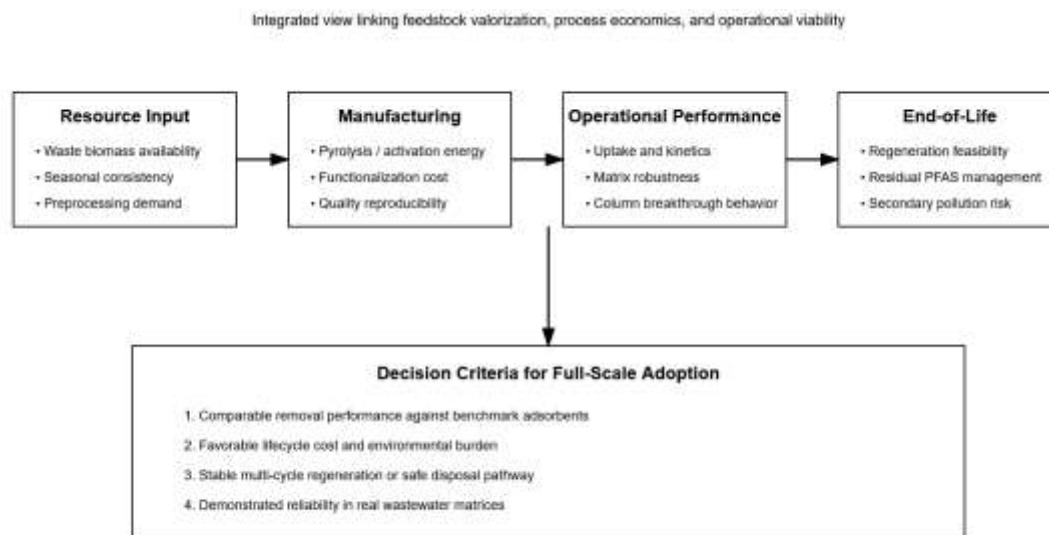


Figure 4. Sustainability and scale-up framework for bio-based adsorbents, linking biomass availability, manufacturing demand, operational performance, regeneration, and end-of-life management to full-scale adoption criteria.

4.4 Challenges, Limitations, and Future Perspectives

Despite promising advancements, the transition of bio-based adsorbents from laboratory-scale innovation to full-scale implementation remains constrained by several interrelated technical and operational challenges. These challenges are not isolated but rather interconnected, spanning material performance, process engineering, and regulatory considerations, thereby necessitating a multidisciplinary approach to solution development.

1. **Variable Performance and Selectivity:** The removal efficiency of bio-based adsorbents can vary significantly depending on the specific contaminant, its concentration, and the water matrix. Short-chain PFAS, for instance, remain particularly challenging to remove, and many bio-based materials exhibit lower efficacy compared to their long-chain counterparts [18]. Enhancing selectivity in complex wastewater environments, where various organic and inorganic co-contaminants compete for adsorption sites, is a persistent hurdle [18].
2. **Regeneration and Stability:** While regeneration methods exist, achieving complete desorption of contaminants, especially PFAS, without compromising adsorbent integrity or generating secondary waste remains problematic [33].

Performance decline over multiple cycles and the energy intensity of thermal regeneration highlight the need for more efficient and sustainable regeneration protocols [33].

3. **Scalability and Standardization:** The transition from laboratory-scale efficacy to industrial-scale application requires robust and standardized production methods for bio-based adsorbents. Variability in biomass feedstock characteristics can impact the consistency and performance of the final product. Addressing these engineering challenges is crucial for broad adoption [22][40].
4. **Cost-Effectiveness for Advanced Materials:** While raw biomass is inexpensive, advanced modifications to enhance performance can increase production costs, potentially diminishing the economic advantage over conventional materials. A thorough techno-economic assessment is needed to ensure long-term affordability and competitiveness [25][40].
5. **Regulatory and Policy Frameworks:** The evolving regulatory landscape for PFAS and ECs necessitates continuous adaptation of treatment technologies. Policies that incentivize the development and deployment of sustainable, bio-based solutions, alongside frameworks for managing exhaust adsorbents, are crucial for progress.

Future research efforts should focus on:

- **Enhanced Specificity:** Developing novel modification strategies to impart higher selectivity for specific PFAS and ECs, potentially through molecular imprinting or targeted functionalization [32][41].
- **Sustainable Regeneration:** Exploring innovative, low-energy regeneration techniques, possibly involving biological processes or advanced oxidation methods integrated with adsorption, to minimize secondary waste and energy consumption [33].
- **Hybrid Systems:** Integrating bio-based adsorbents with other treatment technologies (e.g., membrane filtration, photocatalysis) to create synergistic systems that address a broader spectrum of contaminants and enhance overall removal efficiency [11][42].
- **Computational Modeling:** Leveraging computational approaches, such as machine learning and molecular dynamics simulations, to predict optimal adsorbent designs and understand adsorption mechanisms at a fundamental level, thereby accelerating material development .
- **Real-World Application and Long-Term Studies:** Conducting more pilot-scale and full-scale studies using actual wastewater to validate performance, assess long-term stability, and gather comprehensive cost data under realistic operational conditions [18].

These future directions collectively aim to bridge the gap between laboratory success and widespread practical application, ensuring that bio-based adsorbents can contribute meaningfully to global water security.

5 Conclusion

The increasing prevalence of PFAS and other emerging contaminants in wastewater poses significant environmental and health risks, necessitating the development of advanced and sustainable treatment solutions. Bio-based adsorbents, derived from abundant and renewable resources, present a highly promising avenue to address these challenges. This comprehensive review has underscored their potential as cost-effective, environmentally benign alternatives to conventional treatment methods.

Bio-based materials, including biochar, lignin derivatives, and various agricultural wastes, possess diverse structural properties and surface chemistries that enable effective contaminant sequestration through mechanisms such as hydrophobic interactions, electrostatic attraction, and pore filling. Recent advancements in their design, involving chemical modifications and nanotechnological integration, have significantly enhanced their adsorption capacities and selectivity, even approaching the performance of established adsorbents like activated carbon for certain pollutants. For example, dual-functionalized clinoptilolite zeolites demonstrate comparable PFOA removal efficiencies to GAC.

Furthermore, the inherent sustainability of bio-based adsorbents, coupled with their potential for valorizing waste streams and reducing the environmental footprint of wastewater treatment, positions them as a critical component of future water management strategies. Economic assessments, such as the favorable payback period for modified biochar in industrial wastewater treatment, reinforce their long-term viability [26].

This study provides a comprehensive, mechanism-driven evaluation of bio-based adsorbents for PFAS and emerging contaminant removal, integrating material science, environmental engineering, and sustainability assessment perspectives. By bridging the gap between adsorption mechanisms, material design, and real-world applicability, the findings contribute to advancing next-generation wastewater treatment strategies.

Future progress in this field will depend on the development of highly selective adsorbents, scalable production methods, and integrated treatment systems that combine adsorption with complementary technologies. The incorporation of data-driven approaches, including machine learning and predictive modeling, further offers significant potential to accelerate material optimization and deployment. Collectively, these advancements will be instrumental in addressing the global challenge of persistent water contaminants and achieving sustainable water management goals.

References

- [1] F. Younas *et al.*, “Current and Emerging Adsorbent Technologies for Wastewater Treatment: Trends, Limitations, and Environmental Implications,” *Water*, vol. 13, pp. 215–215, Jan. 2021, doi: 10.3390/w13020215.

- [2] R. Soni, A. K. Pal, P. Tripathi, J. A. Lal, K. Kesari, and V. Tripathi, "An overview of nanoscale materials on the removal of wastewater contaminants," *Applied Water Science*, vol. 10, no. 8. Springer Science and Business Media LLC, Jul. 12, 2020. doi: 10.1007/s13201-020-01275-3.
- [3] T. Jiang, W. Wu, M. Ma, Y. Hu, and R. Li, "Occurrence and distribution of emerging contaminants in wastewater treatment plants: A globally review over the past two decades," *Science of The Total Environment*, vol. 951. Elsevier BV, p. 175664, Nov. 2024. doi: 10.1016/j.scitotenv.2024.175664.
- [4] D. Yadav *et al.*, "Environmental and health impacts of contaminants of emerging concerns: Recent treatment challenges and approaches," *Chemosphere*, vol. 272, pp. 129492–129492, Jan. 2021, doi: 10.1016/j.chemosphere.2020.129492.
- [5] Y. Shen, J. Kang, L. Guo, F. Qiu, F. Yang, and S. Zhang, "Recent progress on the application of MOFs and their derivatives in adsorbing emerging contaminants," *Separation and Purification Technology*, vol. 350, pp. 127955–127955, May 2024, doi: 10.1016/j.seppur.2024.127955.
- [6] S. Kabiri, C. L. Monaghan, D. Navarro, and M. J. McLaughlin, "Hydrophobic interaction is the dominant mechanism of zwitterionic PFAS adsorption to carbon-based sorptive materials in water and soil," *Environmental Science: Water Research & Technology*, vol. 10, no. 2. Royal Society of Chemistry (RSC), pp. 420–430, 2024. doi: 10.1039/d3ew00550j.
- [7] T. Teymourian, T. Teymoorian, E. Kowsari, and S. Ramakrishna, "A review of emerging PFAS contaminants: sources, fate, health risks, and a comprehensive assortment of recent sorbents for PFAS treatment by evaluating their mechanism," *Research on Chemical Intermediates*, vol. 47, pp. 4879–4914, Oct. 2021, doi: 10.1007/s11164-021-04603-7.
- [8] R. Amen, A. Ibrahim, W. Shafqat, and E. B. Hassan, "A Critical Review on PFAS Removal from Water: Removal Mechanism and Future Challenges," *Sustainability*, vol. 15, no. 23. MDPI AG, p. 16173, Nov. 21, 2023. doi: 10.3390/su152316173.
- [9] P. Jerič, B. Likozar, and U. Novak, "Biobased Hydrophobic Solutions for Natural Textiles—Moving Beyond PFAS," *Journal of Composites Science*, vol. 9, no. 2. MDPI AG, p. 81, Feb. 10, 2025. doi: 10.3390/jcs9020081.
- [10] F. Arous, C. Hamdi, S. Bessadok, and A. Jaouani, "Innovative Biological Approaches for Contaminants of Emerging Concern Removal from Wastewater: A Mini-Review," *Zenodo (CERN European Organization for Nuclear Research)*, vol. 13, May 2019, doi: 10.19080/aibm.2019.13.555875.
- [11] S. F. Ahmed *et al.*, "Recent developments in physical, biological, chemical, and hybrid treatment techniques for removing emerging contaminants from wastewater," *Journal of Hazardous Materials*, vol. 416, pp. 125912–125912, Apr. 2021, doi: 10.1016/j.jhazmat.2021.125912.
- [12] Z. Hashmi, A. S. Jatoti, S. Nadeem, A. Anjum, S. M. Imam, and H. Jangda, "Comparative analysis of conventional to biomass-derived adsorbent for wastewater

treatment: a review,” *Biomass Conversion and Biorefinery*, vol. 14, no. 1. Springer Science and Business Media LLC, pp. 45–76, Mar. 03, 2022. doi: 10.1007/s13399-022-02443-y.

[13] I. M. Militao, F. Roddick, R. Bergamasco, and L. Fan, “Removing PFAS from aquatic systems using natural and renewable material-based adsorbents: A review,” *Journal of environmental chemical engineering*, vol. 9, pp. 105271–105271, Feb. 2021, doi: 10.1016/j.jece.2021.105271.

[14] I. M. Militao, F. Roddick, and L. Fan, “Removing PFAS from aquatic systems using natural and renewable material-based adsorbents: A review,” *Figshare*, Nov. 2024.

[15] M. V. Varsha, P. S. Kumar, and B. S. Rathi, “A review on recent trends in the removal of emerging contaminants from aquatic environment using low-cost adsorbents,” *Chemosphere*, vol. 287, pp. 132270–132270, Sep. 2021, doi: 10.1016/j.chemosphere.2021.132270.

[16] I. Bavasso, M. P. Bracciale, F. Sbardella, L. Di Palma, and S. Marco, “Removal of PFAS from wastewater by bio-waste adsorbent: material characterization and adsorption kinetic study,” *Global NEST International Conference on Environmental Science & Technology*. Cosmos S.A. doi: 10.30955/gnc2019.00218.

[17] S. B. Gewurtz, A. S. Auyeung, A. O. De Silva, S. Teslic, and S. A. Smyth, “Per- and polyfluoroalkyl substances (PFAS) in Canadian municipal wastewater and biosolids: Recent patterns and time trends 2009 to 2021,” *The Science of The Total Environment*, vol. 912, pp. 168638–168638, Nov. 2023, doi: 10.1016/j.scitotenv.2023.168638.

[18] E. Gagliano, M. Sgroi, P. P. Falciglia, F. G. A. Vagliasindi, and P. Roccaro, “Removal of poly- and perfluoroalkyl substances (PFAS) from water by adsorption: Role of PFAS chain length, effect of organic matter and challenges in adsorbent regeneration,” *Water Research*, vol. 171. Elsevier BV, p. 115381, Mar. 2020. doi: 10.1016/j.watres.2019.115381.

[19] O. Anifowose, “Augmented Decision Intelligence: Leveraging AI and Predictive Analytics for Executive Strategy Formulation,” *Journal of Computational Analysis and Applications*, vol. 31, no. 3, pp. 750–777, Mar. 2023, [Online]. Available: <https://eudoxuspress.com/index.php/pub/article/view/4136>

[20] M. P. Papini *et al.*, “Adsorption Technology for PFAS Removal in Water: Comparison between Novel Carbonaceous Materials,” *Materials*, vol. 17, pp. 4169–4169, Aug. 2024, doi: 10.3390/ma17174169.

[21] J. Roman, A. J. B. Kemperman, W. van der Meer, and J. A. Wood, “Assessing the viability of bio-based adsorbents for PFAS removal,” *Chemical Engineering Science*, vol. 306, pp. 121215–121215, Jan. 2025, doi: 10.1016/j.ces.2025.121215.

[22] D. Wei *et al.*, “Biochar-based functional materials in the purification of agricultural wastewater: Fabrication, application and future research needs,” *Chemosphere*, vol. 197. Elsevier BV, pp. 165–180, Apr. 2018. doi: 10.1016/j.chemosphere.2017.12.193.

[23] A. S. Jatoi, Z. Hashmi, J. Ahmed, S. A. Mazari, N. M. Mubarak, and M. A. Usto, “Recent Trend and Evaluation of Bio-assisted Adsorbents for the Removal of Emerging Pollutants and Its Adsorption Mechanisms,” *Water, Air, & Soil Pollution*, vol. 234, no. 7.

Springer Science and Business Media LLC, Jun. 21, 2023. doi: 10.1007/s11270-023-06415-4.

[24] C. Wu, M. J. Klemes, B. Trang, W. R. Dichtel, and D. E. Helbling, “Exploring the factors that influence the adsorption of anionic PFAS on conventional and emerging adsorbents in aquatic matrices,” *Water Research*, vol. 182, pp. 115950–115950, May 2020, doi: 10.1016/j.watres.2020.115950.

[25] X. Lei *et al.*, “A review of PFAS adsorption from aqueous solutions: Current approaches, engineering applications, challenges, and opportunities,” *Environmental Pollution*, vol. 321, pp. 121138–121138, Jan. 2023, doi: 10.1016/j.envpol.2023.121138.

[26] A. G. Kumi, M. G. Ibrahim, M. Fujii, and M. Nasr, “Petrochemical Wastewater Treatment by Eggshell Modified Biochar as Adsorbent: A techno-Economic and Sustainable Approach,” *Adsorption Science & Technology*, vol. 2022. SAGE Publications, Jan. 2022. doi: 10.1155/2022/2323836.

[27] I. E. Udofia, “Stochastic Modelling of Falsified Medicine Detection Accuracy Using Blockchain Verification Systems,” *International Journal of Scientific Research in Science and Technology*, p. 940, Dec. 2023, doi: 10.32628/ijrst22913147.

[28] O. A. Salawu, C. I. Olivares, and A. S. Adeleye, “Adsorption of PFAS onto secondary microplastics: A mechanistic study,” *Journal of Hazardous Materials*, vol. 470. Elsevier BV, p. 134185, May 2024. doi: 10.1016/j.jhazmat.2024.134185.

[29] M. B. Ashimolowo, “A Computational Model for Risk-Based Quality Governance Assessment in High-Risk Infrastructure Projects: A Weighted Composite Scoring Approach,” *Journal of Computational Analysis and Applications (JoCAAA)*, vol. 33, no. 08, pp. 8352–8374, Aug. 2024, [Online]. Available: <https://eudoxuspress.com/index.php/pub/article/view/5304>

[30] S.-H. Kim, D.-S. Kim, H. Moradi, Y.-Y. Chang, and J.-K. Yang, “Highly porous biobased graphene-like carbon adsorbent for dye removal: Preparation, adsorption mechanisms and optimization,” *Journal of environmental chemical engineering*, vol. 11, pp. 109278–109278, Jan. 2023, doi: 10.1016/j.jece.2023.109278.

[31] S. Kishore *et al.*, “A comprehensive review on removal of pollutants from wastewater through microbial nanobiotechnology -based solutions,” *Biotechnology and Genetic Engineering Reviews*, vol. 40, no. 4. Informa UK Limited, pp. 3087–3112, Aug. 03, 2022. doi: 10.1080/02648725.2022.2106014.

[32] F. Calore, E. Badetti, A. Bonetto, A. Pozzobon, and A. Marcomini, “Non-conventional sorption materials for the removal of legacy and emerging PFAS from water: A review,” *Emerging Contaminants*, vol. 10, no. 3. Elsevier BV, p. 100303, Sep. 2024. doi: 10.1016/j.emcon.2024.100303.

[33] M. Vakili *et al.*, “Regeneration of exhausted adsorbents after PFAS adsorption: A critical review,” *Journal of Hazardous Materials*, vol. 471, pp. 134429–134429, Apr. 2024, doi: 10.1016/j.jhazmat.2024.134429.

[34] H. Kim, P. G. K. van Groos, Y. Zhao, and A. L.-T. Pham, “Removal of PFAS by hydrotalcite: Adsorption mechanisms, effect of adsorbent aging, and thermal

regeneration,” *Water Research*, vol. 260, pp. 121925–121925, Jun. 2024, doi: 10.1016/j.watres.2024.121925.

[35] A. L. Craighill and J. C. Powell, “Lifecycle assessment and economic evaluation of recycling: A case study,” *Resources, Conservation and Recycling*, vol. 17, no. 2. Elsevier BV, pp. 75–96, Aug. 1996. doi: 10.1016/0921-3449(96)01105-6.

[36] Y. Luo, K. Fu, D. Wang, and J. Luo, “Nanobubble-Driven Interfacial Interactions of Carbon-Based Adsorbents with Legacy PFAS: Impact of Concentration, pH, and Coexisting Ions,” *Environmental Science & Technology*, vol. 59, no. 13. American Chemical Society (ACS), pp. 6900–6914, Mar. 28, 2025. doi: 10.1021/acs.est.4c14726.

[37] Z. Chen, W. Wei, H. Chen, and B.-J. Ni, “Recent advances in waste-derived functional materials for wastewater remediation,” *Eco-Environment & Health*, vol. 1, pp. 86–104, Jun. 2022, doi: 10.1016/j.eehl.2022.05.001.

[38] L. Høiby, J. Clauson-Kaas, H. Wenzel, H. F. Larsen, B. N. Jacobsen, and O. Dalgaard, “Sustainability assessment of advanced wastewater treatment technologies,” *Water Science and Technology*, vol. 58, no. 5. IWA Publishing, pp. 963–968, Sep. 01, 2008. doi: 10.2166/wst.2008.450.

[39] P. H. Nakhate, K. K. Moradiya, H. Patil, K. V. Marathe, and G. D. Yadav, “Case study on sustainability of textile wastewater treatment plant based on lifecycle assessment approach,” *Journal of Cleaner Production*, vol. 245, pp. 118929–118929, Oct. 2019, doi: 10.1016/j.jclepro.2019.118929.

[40] A. Mudhoo, D. Mohan, C. U. Pittman, G. Sharma, and M. Sillanpää, “Adsorbents for real-scale water remediation: Gaps and the road forward,” *Journal of environmental chemical engineering*, vol. 9, pp. 105380–105380, Mar. 2021, doi: 10.1016/j.jece.2021.105380.

[41] P. S. Pauletto and T. J. Bandoz, “Activated carbon versus metal-organic frameworks: A review of their PFAS adsorption performance,” *Journal of Hazardous Materials*, vol. 425, pp. 127810–127810, Nov. 2021, doi: 10.1016/j.jhazmat.2021.127810.

[42] K. Nelson, A. C. Mecha, H. M. Samuel, and Z. A. Suliman, “Recent Trends in the Application of Photocatalytic Membranes in Removal of Emerging Organic Contaminants in Wastewater,” *Processes*, vol. 13, no. 1. MDPI AG, p. 163, Jan. 09, 2025. doi: 10.3390/pr13010163.