

OIL REMOVAL FROM WASTEWATER USING BIOMASS-DERIVED ACTIVATED CARBON: A SYSTEMATIC REVIEW OF SYNTHESIS, PERFORMANCE, AND MECHANISMS

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ABSTRAK

Air limbah yang mengandung minyak menimbulkan risiko lingkungan dan kesehatan yang serius, sehingga menciptakan kebutuhan akan teknologi pengolahan yang berkelanjutan dan efektif. Tinjauan sistematis ini menunjukkan kinerja karbon aktif yang berasal dari biomassa untuk penghilangan minyak dan kontaminan organik, dengan fokus pada sintesis, mekanisme adsorpsi, regenerasi, serta peningkatan skala. Mengikuti kerangka kerja PRISMA, 1.240 artikel Scopus disaring dan 64 studi yang diterbitkan antara 2023 dan 2025 disertakan. Literatur yang ditinjau menunjukkan bahwa karbon aktif yang berasal dari biomassa dapat mencapai efisiensi penghilangan lebih dari 90% dalam kondisi laboratorium terkendali. Aktivasi kimia menggunakan KOH, H₃PO₄, atau ZnCl₂ umumnya menghasilkan luas permukaan yang tinggi dan porositas yang berkembang dengan baik. Namun, kinerja adsorpsi juga dipengaruhi oleh distribusi ukuran pori-pori, kimia permukaan, hidrofobisitas, pH, dosis adsorben, konsentrasi kontaminan, serta waktu kontak. Adsorpsi umumnya mengikuti kinetika orde kedua semu dan isothermal Langmuir, yang melibatkan pengisian pori-pori, gaya van der Waals, interaksi hidrofobik, daya tarik elektrostatis, ikatan hidrogen, interaksi π - π , dan kemisorpsi. Keterbatasan utama mencakup penurunan kinerja pada air limbah nyata, hilangnya kapasitas selama regenerasi, serta bukti skala percontohan yang terbatas. Penelitian di masa depan harus memprioritaskan validasi aliran berkelanjutan, regenerasi energi rendah, penilaian teknokonomi, dan analisis siklus hidup.

Kata Kunci: Karbon aktif biomassa, PRISMA, air limbah berminyak, penghilangan minyak, adsorpsi, regenerasi

ABSTRACT

Oil-contaminated wastewater poses serious environmental and health risks, creating a need for sustainable and effective treatment technologies. This systematic review evaluates the performance of biomass-derived activated carbon for oil and organic contaminant removal, focusing on synthesis, adsorption mechanisms, regeneration, and scale-up. Following the PRISMA framework, 1,240 Scopus records were screened, and 64 studies published between 2023 and 2025 were included. The reviewed literature shows that biomass-derived activated carbon can achieve removal efficiencies above 90% under controlled laboratory conditions. Chemical activation using KOH, H₃PO₄, or ZnCl₂ generally produces high surface area and well-developed porosity. However, adsorption performance is also influenced by pore-size distribution, surface chemistry, hydrophobicity, pH, adsorbent dosage, contaminant concentration, and contact time. Adsorption commonly follows pseudo-second-order kinetics and the Langmuir isotherm, involving pore filling, van der Waals forces, hydrophobic interactions, electrostatic attraction, hydrogen bonding, π - π interactions, and chemisorption. Major limitations include reduced performance in real wastewater, capacity loss during regeneration, and limited pilot-scale evidence. Future research should prioritize continuous-flow validation, low-energy regeneration, techno-economic assessment, and life-cycle analysis.

Keywords: biomass-derived activated carbon, PRISMA, oily wastewater, oil removal, adsorption, regeneration.

INTRODUCTION

Activated carbon is widely known as a versatile adsorbent capable of removing various contaminants from air and water. Conventionally, activated carbon is produced from non-renewable raw materials, such as synthetic precursors, via high-temperature processes that require substantial energy. Several studies have shown that, as a sustainable precursor, activated carbon derived from biomass has significant adsorption capacity for a variety of pollutants, including oil-containing pollutants. This is due to its porous structure and functional groups (Khum-in et al., 2025; Kanakaraju et al., 2025; Mahmood et al., 2025). Chemical adsorption gained dominance, as supported by the citation review results. This has led to conflicting debates regarding the adsorption mechanism (Manaf et al., 2025; Chyad et al., 2025), while others emphasize the importance of physical adsorption (Nagy et al., 2025; Khaphong et al., 2025). According to the paper review, the results include 80% batch adsorption experiments, kinetic modeling using second-order pseudo-first-order equations, and isotherm analyses using the Langmuir and Freundlich models. It is possible to discuss a hybrid model that transitions from basic carbonization to complex chemical activation with KOH or H₃PO₄. This process could demonstrate greater efficiency in removing oil pollutants from wastewater (Hafizah et al., 2025; Amari et al., 2023).

A major global problem is caused by businesses discharging wastewater containing oil pollutants into the environment. Adverse impacts will be observed not only in biodiversity ecosystems but also in increased adverse risks to human health. Therefore, the researchers emphasize the need for long-lasting cleaning technologies to address climate change (Amari et al., 2023). In 1918, the theory of pollutant elimination emerged: adsorption. This model was proposed by Langmuir, who postulated that a single layer covers a homogeneous surface. The Langmuir model was the prevailing theory at the time, so there was a theoretical development to better account for complex wastewater matrices by combining the heterogeneously layered Freundlich model with the Dubinin-Radushkevich pore-filling mechanism. These theoretical considerations are carried out by contemporary extension using thermodynamic analysis to assess the endotherm and spontaneity of the oil absorption process. These theories support the production of activated carbon by estimating the interaction energies between functional groups and adsorbate molecules. The researchers improved predictive modeling for practical applications, moving from simple physisorption models to more complex chemical models (Mahmood et al., 2025).

Oil contaminants in wastewater pose a special problem because they exist as an elusive emulsion, classified as an indecipherable hydrocarbon. The toxic nature of oil-contaminated wastewater disrupts the endocrine systems of living beings and accumulates in the food chain, thus requiring swift action to comply with strict environmental regulations. Research results from wastewater left over from the bioethanol and tanning industries that are not managed indicate that it can pollute soil and groundwater. This problem can worsen environmental damage if not handled. The ability to handle wastewater without producing additional pollutants is a requirement for effective adsorbents (Khum-in et al., 2025). The environmental sector is currently encouraging the implementation of a circular economy, which is an economic model

that uses a system approach in production to consumption activities, which minimizes the use of resources and waste generation, maintains material usability, and is regenerative. For example, converting the shells of palm kernels and cassava residue into activated carbon for adsorption, because it has a larger surface area of 1000 m²/g and the porosity can be adjusted. These results are superior to conventional synthetic adsorbents in capturing non-polar oil molecules. This condition reduces the use of chemicals in wastewater treatment, in line with the Sustainable Development Goals. These new innovations help protect biodiversity by reducing the damage caused by oil contamination to natural ecosystems. Practitioners found that these materials were not useful when the pH and temperature of industrial wastewater changed (Hafizah et al., 2025).

Due to the lack of comprehensive research on activated carbon derived from biomass specifically for the removal of oil content in wastewater, the authors reviewed 64 papers focusing on oil absorption. The purpose of the review is to understand the method's success and the factors that influence it, so it can be used in the future. This review emphasizes the urgency of this issue and then proposes a much better synthesis path. In theory, this approach could improve the adsorption model, especially for oil-containing systems. From a practical perspective, industries under pressure from environmental regulations can obtain a more cost-effective solution (Kanakaraju et al., 2025).

The main research question (PRQ) driving this review is: how effective is activated carbon derived from biomass in removing oil contaminants from wastewater, and what factors influence its adsorption efficiency? This question is appropriate because it focuses on the source of biomass and specific oil metrics, such as capacity and kinetics. To answer this question, the literature can be examined, and experimental data on the adsorption capacity of different materials can be used. It is crucial for science and practice to develop sustainable materials engineering for pollution control. The range of reviews is precise, neither so broad as to lose focus nor so narrow as to miss important factors. The presentation is organized, the language is clear, and the structure makes it easy to look at the different factors that affect success in a structured way. (Manaf et al., 2025).

PRQ1 is one of three secondary research questions (SRQs). SRQ1 asks: Which synthesis methods and starting materials have the best oil-removal adsorption capacity? Synthesis methods, such as using KOH and waste materials like rice straw, are considered, making it specific by linking the methods to capacity results. SRQ2: How does activated carbon from biomass absorb oil, and how quickly does the process happen? This discusses the differences between physical and chemical adsorption. To address this issue, the kinetic model from previous research can be used. SRQ3: What problems and prospects arise as a result of developing and regenerating these adsorbents for use in industry? This highlights the issue of reuse, which relates to adapting completeness to specificity and practical implementation (Chyad et al., 2025). The reason are actionable and grounded in the literature, these questions meet the evaluation criteria. Specificity ensures research focused on scalability, synthesis, and mechanisms. Empirical support for the availability of literature is provided by the 64 abstracts reviewed. New ideas in wastewater engineering and green chemistry are driven by relevance.

To prevent something from becoming too general or too specific, use balanced coverage. A systematic formulation logically organizes the review, starting with the methods and ending with the applications (Nagy et al., 2025).

The need for research is growing as the energy industry is expected to generate 20 million tons of oily wastewater by 2030. Adsorption studies focusing on oil have limitations, underscoring why this synthesis should serve as the basis for policy and technology adoption. Making activated carbon from biomass waste is a solution that will reduce our dependence on fossil fuels. One advantage, according to economic studies, is that treatment costs are 30 to 50 percent lower than with commercial carbon. This method encourages the use of renewable resources, contributing to international sustainability goals (Khaphong et al., 2025).

METHODOLOGY

Research Design and Approach

The method used in this study is the Systematic Literature Review (SLR) Method. The SLR method is used to identify, review, evaluate, and interpret all available research within a topic area of interest to the phenomenon, with specific research questions relevant to the study. Using the SLR Method, journals can be systematically reviewed and identified, following the set steps or protocols at each stage. The results of the study show that the dominant platform for information system development is website-based, while the dominant method is the structured method. This review uses the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method. The purpose of using PRISMA is to create a clear review framework for the literature study being researched, from the beginning of the search through the selection process to the final result. By using the PRISMA method, it is hoped that researchers or readers can ensure that the selection process is carried out objectively and can be traced. The specified inclusion criteria encompassed articles published up until December 31, 2025, written in English, and concentrating on the theme of Activated Carbon Adsorbent. This study thus offers the inaugural systematic review of the use of activated carbon adsorbents for oil-containing wastewater. Rather than engaging in broad discussions concerning oily wastewater treatment, this review meticulously examines the intricate relationship between the distinct physicochemical characteristics of these organophosphorus compounds, the challenging aqueous environment, and the adsorption efficacy of activated carbon. By adopting a systematic approach.

PRQ : How effective is biomass-derived activated carbon in removing oil contaminants from wastewater, and what factors influence its adsorption performance?

SRQ1: What synthesis methods and starting materials have the best oil removal adsorption capacity?

SRQ2: How does activated carbon from biomass absorb oil and how quickly does the process happen?

SRQ3: What problems and prospects arise as a result of developing and regenerating these

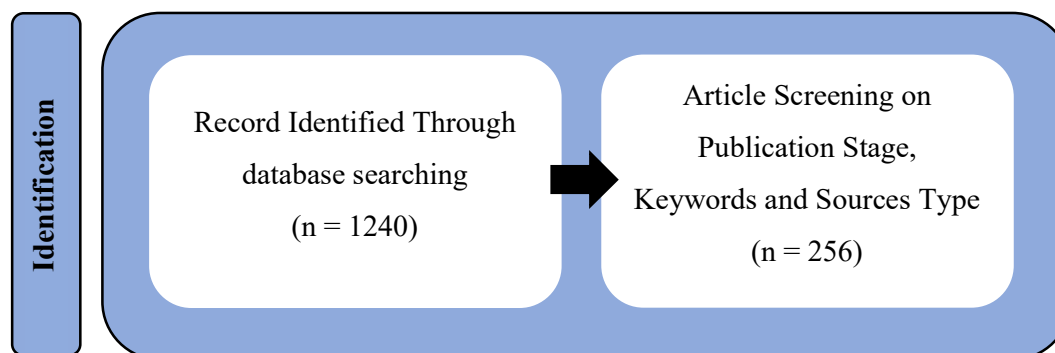
adsorbents for use in industry?

Data Sources and Search Strategy

The literature search was executed in the Scopus database, renowned for its extensive indexing of high-quality peer-reviewed journals across scientific disciplines. A targeted search strategy was developed using Boolean operators to combine key conceptual terms. The search string included variants of: ("activated carbon" OR "activated charcoal" OR "active carbon" OR "granular activated carbon" OR "powdered activated carbon" OR "AC" OR "porous carbon" OR "AC adsorbent" OR "carbonaceous adsorbent") AND (adsorb OR adsorption OR "sorption" OR "removal" OR "elimination") AND (wastewater OR "industrial wastewater" OR "hydrometallurgical wastewater" OR "hydrometallurgical effluent" OR "leach solution" OR "metal-bearing wastewater" OR "spent electrolyte"). This search was applied to article titles, abstracts, and keywords to maximize relevance while maintaining scope. The initial search, conducted in January 2026, yielded 1,240 records for subsequent screening, as documented in the PRISMA flow diagram.

Eligibility Criteria and Study Selection

The study selection process adhered strictly to the PRISMA flow diagram. Following the removal of duplicates, records were screened at two levels: first by title/abstract and then by full-text assessment. Inclusion criteria were defined *a priori*: (1) primary research articles published in English between 2023 and 2025; (2) focus on the synthesis and/or application of biomass-derived AC; (3) investigation of oil/hydrocarbon adsorption from aqueous environments; and (4) reporting of quantitative performance data such as adsorption capacity or removal efficiency, with bibliometric analysis performed using VOSViewer. Studies were excluded if they focused solely on gaseous adsorption, non-biomass precursors, or general wastewater treatment without specific oil adsorption metrics. Furthermore, the subject area was filtered to include Environmental Science, Chemistry, Chemical Engineering, and Materials Science to maintain technical relevance.



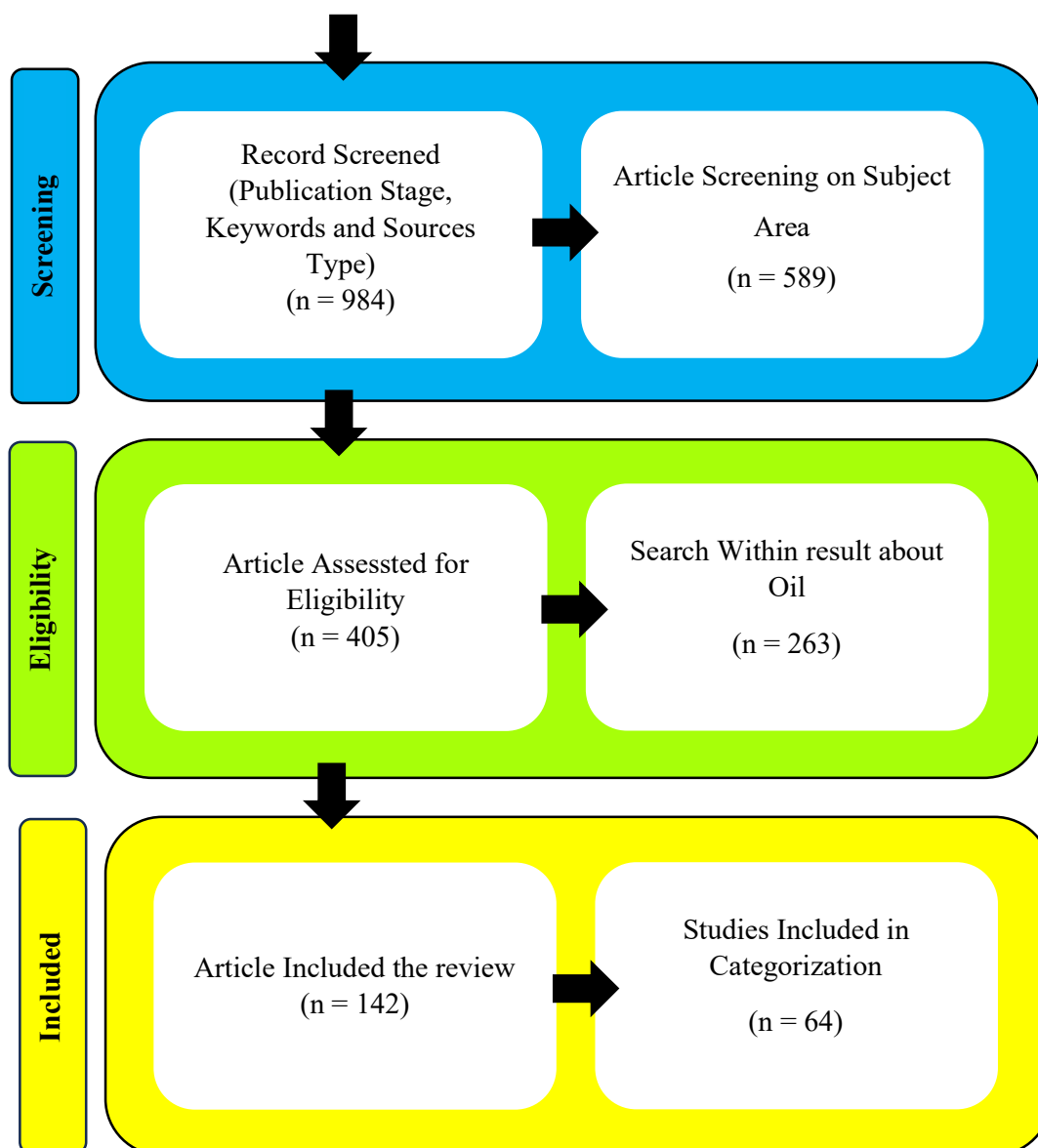
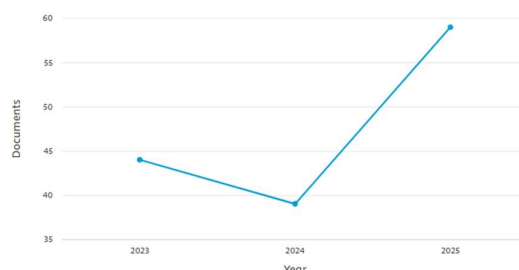


Figure 1. Systematic Literature Review Information Using PRISMA

Data Extraction and Synthesis

Data from the 64 included studies were extracted using a standardized coding form. Extracted information encompassed precursor material, synthesis method (pyrolysis temperature, activating agent), characterized adsorbent properties (surface area, pore structure, functional groups), experimental conditions (oil type, concentration, pH), adsorption performance metrics (capacity, kinetics, isotherm models), and proposed mechanisms. A thematic synthesis approach was then employed to analyze the data in direct relation to the secondary research

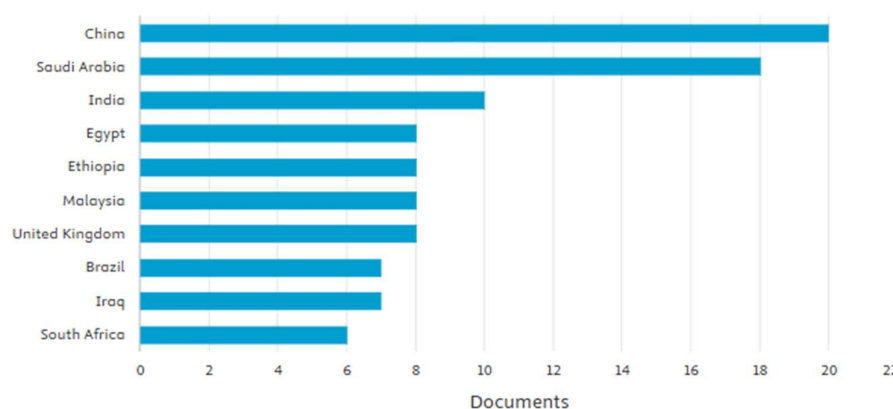
questions (Booth et al., 2022). This involved categorizing findings into coherent themes—such as synthesis-performance relationships, mechanistic insights (e.g., physisorption, hydrophobic interaction), and technological scalability—to provide an integrated, narrative answer to the primary research question regarding the effectiveness and influencing factors of biomass-derived AC for oil removal.



Source : Scopus Database

Figure 2. Number of Document by Year of Activated Carbon Adsorbent

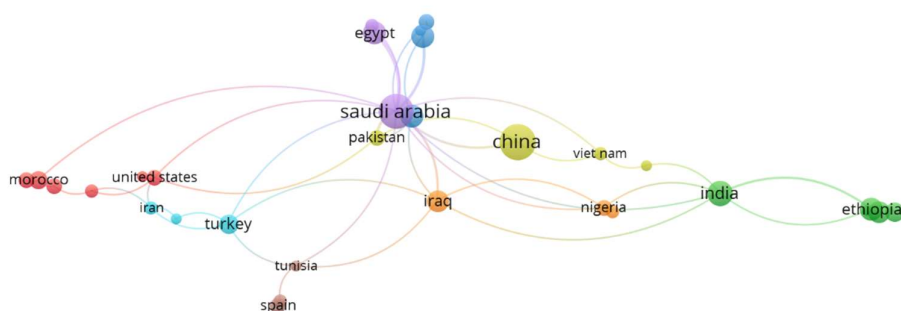
The initial limit for paper publication is 2023 with the results of 44 papers on activated carbon adsorbents. Meanwhile, in 2024 it will decrease to 39 papers. Screening data from Scopus shows a significant increase in 2025 for papers on activated carbon adsorbents with 59 papers.



Source : Scopus Database

Figure 3. Number of Articles by Country of Territory (Top 10 Country)

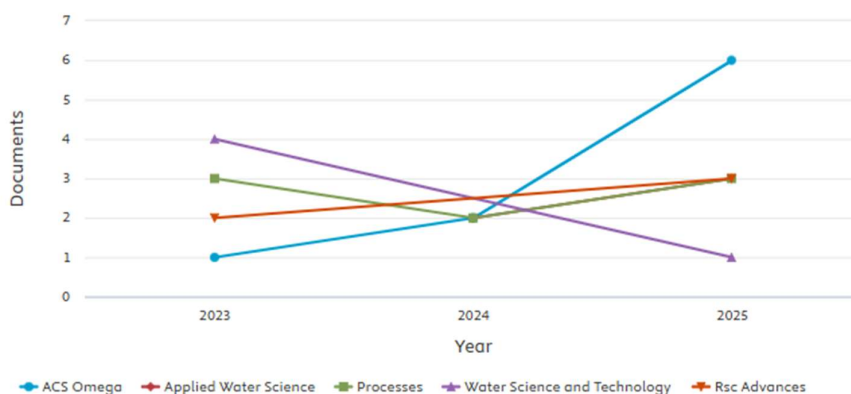
The analysis of the distribution of activated carbon adsorbents in the articles was conducted by categorizing the articles according to classification criteria such as keywords, subject area, and source, with the constraint that similar articles were grouped within each classification. The allocation of scholarly inquiries pertinent to activated carbon adsorbents by nation or geographical area among the top 10 countries is dominated by China with 20 articles, Saudi Arabia with 18 articles, India with 10 articles, Egypt, Ethiopia, Malaysia, and the United Kingdom with 8 articles, Brazil and Iraq with 7 articles, and South Africa with 6 articles (See Figure 3).



Source : Scopus Database

Figure 4. Network Country Visualization

The network country visualization for activated carbon adsorbents shows that China dominates in article publication. China dominates in activated carbon adsorbent research, but its dominance is more evident in its central position than in the intensity of collaboration. Saudi Arabia in the network country visualization shows more collaboration with countries in the Middle East and northern Africa.



Source : Scopus Database

Figure 5. Document per Year By Source

The allocation of inquiries about activated carbon adsorbents by source from 2023 to 2025 is predominantly ACS Omega (9 documents), Applied Water Science (5 documents), Processes Journal (8 documents), Water Science and Technology (5 documents), and RSC Advances (5 documents).

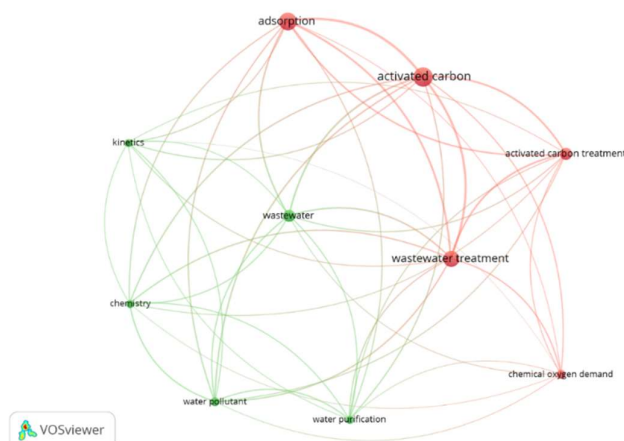


Figure 6. Co-occurrence Framework and Representation of Key Terms

From Figure 6, the occurrence of activated carbon (77), wastewater treatment (56), adsorption (64), activated carbon treatment (30), wastewater (31), water pollutant (18), chemistry (15), water purification (14), kinetics (14) and chemical oxygen demand (17).

Table 1. Keywords by Authors

Rank	Keyword	Total Link Strength
1	Activated Carbon	254
2	Wastewater Treatment	221
3	Adsorption	202
4	Activated Carbon Treatment	148
5	Wastewater	148
6	Water Pollutant	146
7	Chemistry	122
8	Water Purification	113
9	Kinetics	78
10	Chemical Oxygen Demand	68

Based on the mapping outcomes and an examination of the investigation, a deficiency has been recognized in previous research, where the prior studies were conducted on activated carbon adsorption in wastewater treatment. This study should focus on water purification and on controlling chemical oxygen demand. This study can address gaps in previous research and provide more comprehensive information on the outcomes of developing and regenerating these adsorbents for industrial use.

RESULTS

Descriptive Phase: Characteristics of the Reviewed Literature

This systematic review includes 64 studies published between 2023 and 2025 and focuses on

the use of activated carbon (AC) derived from various biomass and waste precursors for liquid waste remediation. The essence of the literature review analysis is the handling of wastewater contaminated by oil. The results show significant contributions from the Asian, Middle Eastern, and European regions. The region shows widespread conditions that require low-cost adsorbents. The study uses a circular economy approach, meaning the precursors used for carbon activation are environmentally friendly. Precursors for carbon activation can be derived from agricultural waste, such as rice husks, coconut shells, corn cobs, and walnut husks. In addition to agricultural waste, industrial byproducts and invasive species can also be used as precursors for carbon activation. (Khum-in et al., 2025; Zayed et al., 2025; Tran et al., 2024).

Experimentation is a methodological approach used to determine the optimal conditions of batch adsorption. The optimal conditions in question are the pH, reaction time, dosage, and concentration used in the experiment. This was adjusted to Langmuir and Freundlich isothermal model data and kinetics (pseudo-first-order, pseudo-second-order). The relationships among adsorbent morphology, surface chemistry, and performance were investigated using surface area analysis (BET), SEM, FTIR, and XRD. While most studies operate at a laboratory scale, a growing number investigate continuous-flow systems, regeneration cycles, and composite materials, indicating an evolution towards assessing practical applications (Song & Tashmukhamed, 2025; Khaophong et al., 2025). This body of literature provides a robust foundation for analyzing the effectiveness of biomass-derived activated carbon for oil removal, as synthesized in the following sections.

Analytical Phase: Addressing the Secondary Research Questions

SRQ1: Synthesis Methods and Precursor Materials for Optimal Oil Adsorption

The formation of activated carbon from biomass determines the pore shape and chemical properties that affect the oil absorption capacity of wastewater. Activated carbon with good oil-absorption properties is produced in two stages: the first is carbonization, in which the raw materials are heated, and the second is chemical and physical activation. Chemical activation is performed to create a pore structure with a large specific surface area, usually using an activating agent. The agents used are KOH, H₃PO₄, and ZnCl₂. One of the results of the literature review obtained is that carbon activation using fox nutshell activated with ZnCl₂ produced a specific surface area of 2408.9 m²/g. The specific surface area yield of 2408.9 m²/g is considered high, indicating a strong adsorption capacity for oily organic pollutants. (Srivastava et al., 2025). Likewise, when charcoal powder waste is used as a carbon-activation material, it must be combined with bitumen. The process for activating charcoal powder waste with bitumen uses steam and produces hierarchically porous carbon (HPC). The specific surface area of the combination is 1299.75 m²/g, which is categorized as quite high. The category shows effectiveness in adsorption (Yin et al., 2023).

The choice of precursor is equally vital. Agricultural waste can be used as precursors to produce activated carbon, such as rice husks and coconut shells. Rice husks and coconut shells are most commonly used because they are readily available and contain lignocellulose. Lignocellulose is a natural structure of plant cell walls that has three main components, namely cellulose,

hemicellulose, and lignin. The three main components of lignocellulose are important for carbon activation because, when heated, they will produce porous carbon that is not easily destroyed (Rabah & Ashour, 2024; Tomon et al., 2023).

There is also a more innovative study, which has succeeded in converting a mixture of plastic waste (AC-CPW) into an effective adsorbent. Activated carbon produced from a plastic waste mixture (AC-CPW) has a specific surface area of 816 m²/g, as evidenced by its ability to remove color and lignin from wastewater. In addition, it shows the potential for handling emulsified oily waste (Gupta et al., 2024). Research conducted by Song and Tashmukhamed in 2025 compared composite adsorbents for oil removal. The study found that carbon-nanoparticle composites were superior to activated carbon. The adsorbent capacity reached 160.5 mg/g. These findings highlight the trend that biomass-derived activated carbon composition, when enhanced with nanoparticles or polymers, can improve selectivity, capacity, and oil-contaminant removal. In addition, it can overcome the limitations of pure activated carbon, which initially had only low selectivity and poor reusability (Amari et al., 2023; Song & Tashmukhamed, 2025).

SRQ2: Predominant Adsorption Mechanisms and Kinetics for Oil Uptake

Oil adsorption on activated carbon derived from biomass occurs via two main mechanisms: physisorption and chemisorption. This process is described using a second-order pseudo-kinetic model for oil absorption by activated carbon. The dominant mechanism in this process is physisorption, driven by van der Waals forces and hydrophobic interactions between oil molecules and the surface of activated carbon. The fission mechanism plays a role in the adsorption of non-polar oil components. Activated carbon derived from biomass has a pore structure that favors adsorption. These pores are classified into two types: mesopores and macropores. Research on hierarchically porous carbon shows that macropores function as transport channels. A transportation channel is the place where oil molecules move into activated carbon. In addition, the micropore serves as an adsorption site, allowing oil to enter the activated carbon more quickly and thereby improving adsorption efficiency (Yin et al., 2023). The surface of biomass-activated carbon is hydrophobic. Hydrophobic properties are due to the high carbon content and the limited presence of oxygen functional groups. This supports the process of adsorption of oil from wastewater. Hydrophobic properties allow activated carbon to attract and retain oil molecules that are insoluble in water, thereby improving adsorption ability.

Chemisorption plays a significant role when the activated carbon surface contains specific functional groups. Electrostatic interactions can occur on the surface of activated carbon and polar components in oil emulsions. The hydrogen-bonding mechanism and the increased electrostatic attraction in carbon nanoparticle composites and MOF-Polymers can be used for oil absorption. (Song & Tashmukhamed, 2025). In a consistent kinetic analysis, it was found that the adsorption process occurred quickly and then gradually slowed. This happens because, at the beginning of the adsorption process, many pores are available; once some of them are filled, the adsorption rate slows. Second-order pseudo-models are often present in studies and show the most suitable model as a velocity-limiting measure involving chemisorption or the

exchange of adsorbent and adsorbate electrons. (Fito et al., 2023; Rabah & Ashour, 2024). The adsorption rate is affected by the amount of activated carbon available as an adsorbent and the concentration of the oil acting as an adsorbate in the system.

SRQ3: Challenges and Opportunities in Scaling Up and Regeneration

The results of the literature review from several studies show promising potential in terms of carbon activation. Although the results of laboratory experiments show satisfactory results, the challenges ahead are still very significant to increase the activated carbon potential of biomass. These challenges still need to be further managed for the treatment of oil-contaminated industrial wastewater so as not to disturb the environmental balance. One of the key gaps identified is the lack of cost-benefit analysis and comprehensive life-cycle analysis for most adsorbents used. Although the cost of the precursors used is relatively low, for the activation process there is an additional cost. In addition to the additional costs incurred for chemical activation and other processes, there is a need for large-scale measurement of secondary waste streams (Khum-in et al., 2025). The performance of the use of activated carbon in the actual condition of industrial wastewater is still lacking. A number of studies still have a tendency to use only a mixture of synthetic oil and water. This tends to ignore the effects of surfactants, salt content, and other contaminants present in industrial wastewater. Without paying attention to this, there will still be gaps in the adsorption process or the chemical conditions of the water surface. (Song & Tashmukhamed, 2025).

The recycling and regeneration of adsorbents have an impact on economic sustainability. The success of multi-cycle adsorbent regeneration has been demonstrated in research. MOF-polymer composite is an example with 90% effectiveness after 3 adsorption-desorption cycles (Song & Tashmukhamed, 2025). In addition, the magnetic activated carbon (MAC) of the walnut husk has a reuse rate of 80,5% after ten adsorption-desorption cycles (Yimin et al., 2025). As found in existing research, the magnetic function provides an easy separation method with a simple regeneration process (Yimin et al., 2025; Guesmi et al., 2025). Regeneration efficiency may decrease over the course of the cycle due to pore blockages or irreversible chemical bindings. Therefore, regeneration techniques need further development for more efficient and low-energy results (e.g., cold atmospheric plasma, as explored by Stavrinou et al., 2023). In addition to the batch system that has been used so far, there is a need to increase the scale of adsorbent production and design of adsorption columns in the continuous flow process systematically. In this case, the solution or liquid containing the contaminants will continue to flow through the activated carbon adsorbent medium for a long time. It is hoped that continuous flow can change the direction of future research by developing mass adsorbent production and designing more efficient and practical systems on an industrial scale (Zayed et al., 2025; Tran et al., 2024).

Interpretive Phase: Synthesis and Unexplored Patterns

In accordance with the findings of the analysis results, the maximum oil adsorption capacity is not only affected by the high surface area of BET but also the surface chemistry and pore structure. Although the surface area is more than 1000 m²/g, the surface chemistry of the adsorbent determines the adsorption ability. Likewise, the pore structure determines the

effectiveness in oil absorption. Determining the pore structure of an adsorbent should consider its precursors and activation methods. The activation process produces a mixture of pores, namely micropores, mesopores and macropores. This pore result is what provides an advantage in increasing adsorption capacity. In addition, the functional group of the adsorbent surface also affects its effectiveness. For example, hydrophilic groups are useful for absorbing oil and hydrophobic groups are more effective for heavy metals. Therefore, the combination of the two will result in a more efficient adsorption performance in addressing various types of contaminants than unmodified activated carbon with a high specific surface area. In other words, although surface area is an important factor, the regulation of pore structure and the chemical properties of the customized surface will determine the effectiveness of the adsorption process (Song & Tashmukhamed, 2025).

One important but under-appreciated pattern is the potential trade-off between adsorption capacity and mechanical stability. This is especially true in composite adsorbents in continuous flow systems. Although many studies report high adsorption capacity in composite adsorbents, there is a lack of discussion about the long-term physical integrity of these adsorbents. Especially when the material is exposed to hydrodynamic stresses in the column during the continuous flow process. This voltage can affect the physical strength of the adsorbent which risks reducing the effectiveness of adsorption. Most studies focus only on adsorption capacity without considering the saturation point of the adsorbent against oil contaminants. One solution that can be considered is thermal regeneration. Thermal regeneration can restore adsorption capacity and recover energy. However, thermal regeneration needs more research to ensure efficiency at scale. In addition, the safe disposal of used adsorbents needs to be carried out to create a sustainable and environmentally friendly treatment system. In the literature review, there is still not much exploration related to the management of the used adsorbent and there needs to be further study (Amari et al., 2023).

Table 2 Synthesis of Research Questions, Key Findings, and Supporting Evidence
on Biomass-Derived Activated Carbon for Contaminant Removal

Research Question	Key Findings	Supporting Evidence
PRQ: How effective is biomass-derived activated carbon for removing oil and organic contaminants?	It is highly effective under laboratory conditions. Its performance is mainly influenced by surface area and porosity, surface chemistry, pH, adsorbent dosage, and contact time. Its effectiveness in real wastewater remains less established.	Removal efficiencies often exceed 90%, but performance may decline in real wastewater (Sun et al., 2023; Mengistu et al., 2023; Azarshab et al., 2024).
SRQ1: Which synthesis methods and precursors produce the highest adsorption capacities?	Chemical activation using KOH, H ₃ PO ₄ , or ZnCl ₂ generally produces higher surface area and porosity. Doping and composite formation can further improve adsorption performance.	KOH activation: 973 m ² /g (Khan et al., 2023); H ₃ PO ₄ activation: 94.6% phenol removal (Wedian et al., 2023); oil-sludge-derived activated carbon: 406.8 mg/g (Amari et al., 2023); N-doped carbon: 496.53 mg/g (Ren et al., 2025).
SRQ2: What are the dominant adsorption mechanisms and models?	Adsorption kinetics commonly follow the pseudo-second-order model, while equilibrium data often fit the Langmuir isotherm. Mechanisms include pore filling, van der Waals forces, electrostatic attraction, hydrogen bonding, π - π interactions, and complexation.	PSO model with $R^2 > 0.99$ (Fito et al., 2023; Mengistu et al., 2023); Langmuir model for metals and dyes (Anisuzzaman et al., 2023); π - π and electrostatic interactions (Stavrinou et al., 2023; Bautista Quispe et al., 2024).
SRQ3: What are the challenges and opportunities for regeneration and scale-up?	Major challenges include adsorption-capacity loss after regeneration, lower performance in complex wastewater, and limited pilot-scale studies. Opportunities include hybrid treatment systems, magnetic activated carbon, and reuse of spent adsorbents.	Efficiency may decrease from 93% to 21% after seven cycles (Worku et al., 2023); hybrid systems achieved 66% COD removal (Sever et al., 2024); magnetic activated carbon enables easier separation (Yimin et al., 2025); plasma regeneration recovered about 35% of capacity (Stavrinou et al., 2023).

DISCUSSION

Presentation of the Discussion Framework

This discussion synthesizes the findings from 64 recent studies (2023-2025) to critically address the Primary Research Question (PRQ) and its three Secondary Research Questions (SRQs). The structure is designed to move from the fundamental aspects of material synthesis and performance (SRQ1 & SRQ2) towards the practical challenges of implementation (SRQ3), culminating in an integrated answer to the PRQ. The analysis will not merely recount findings but will engage in a dialectical examination of the literature, identifying consensus, contradictions, and critical knowledge gaps. A unique position of this review is its concurrent focus on the efficacy of biomass-derived activated carbon (AC) for oil removal and the often-overlooked scalability and lifecycle considerations that determine its practical viability. The discussion is framed within the broader context of circular economy principles and the urgent need for sustainable water treatment technologies that are both effective and economically feasible for industrial practitioners.

Synthesis Methods and Precursor Efficacy (Addressing SRQ1)

The literature reveals a strong consensus that the adsorption capacity for oil contaminants is intrinsically linked to the synthesis pathway and the chemical-physical properties of the precursor biomass. Chemical activation, particularly using KOH, ZnCl₂, and H₃PO₄, consistently outperforms physical activation in developing microporosity and achieving high specific surface areas (SSA), which are critical for oil adsorption (Khan et al., 2023; Yin et al., 2023). For instance, KOH activation of landscape biomass waste yielded an SSA of 973.21 m²/g, directly correlating with high adsorption capacity (Khan et al., 2023). Similarly, the synergistic pyrolysis and steam activation of bitumite with waste powder char produced hierarchical porous carbons (HPCs) with an SSA up to 1299.75 m²/g, significantly enhancing methylene blue (a model organic contaminant) adsorption (Yin et al., 2023). The selection of precursor is equally pivotal. Agricultural wastes like rice husk, coconut shells, and soybean straw are predominant due to their lignocellulosic structure, low cost, and global abundance (Wedian et al., 2023; Tomon et al., 2023; Jiang et al., 2023). However, more innovative precursors such as oil sludge itself are being explored for waste valorization, demonstrating an iodine number of 406.8 mg/g and 94% treatment efficiency, thus closing the waste loop (Amari et al., 2023).

The critical dialogue here centers on optimizing the activation process. While high SSA is a primary target, an exclusive focus on maximizing SSA can be misleading. The pore size distribution must be compatible with the target oil molecules. Oil constituents often have larger molecular sizes than simple dyes or metals; therefore, a balance of micro- and mesopores is essential for effective diffusion and adsorption. Studies on composite materials, such as the polyurethane foam-activated carbon (PUAC) composite, highlight a strategic shift from mere surface area maximization towards engineering functional composites that enhance practicality—ease of handling, separation, and mechanical stability—sometimes at the cost of absolute SSA (Tomon et al., 2023). Furthermore, the modification of AC with magnetic

components (e.g., Fe_3O_4) or heteroatom doping (e.g., Nitrogen) introduces secondary functionalities that improve separability or surface chemistry, respectively (Kusdarini et al., 2024; Ren et al., 2025). This evolution from simple activated carbons to tailored, multifunctional adsorbents represents a significant advancement in addressing SRQ1, moving beyond "highest capacity" to "most fit-for-purpose" material design.

Adsorption Mechanisms and Kinetic Dominance (Addressing SRQ2)

The analysis of adsorption mechanisms and kinetics across the reviewed studies points to a remarkably consistent narrative: oil and organic contaminant adsorption onto biomass-derived AC is predominantly governed by chemisorption, as evidenced by the widespread and superior fit of the pseudo-second-order (PSO) kinetic model. This model's high correlation coefficients (often $R^2 > 0.99$) indicate that the rate-limiting step involves valence forces through sharing or exchange of electrons between the adsorbent surface and the adsorbate (Fito et al., 2023; Mengistu et al., 2023; Jiang et al., 2023). For instance, the adsorption of chromium and phenol by various ACs was best described by PSO kinetics, underscoring the chemical nature of the binding process (Fito et al., 2023; Wedian et al., 2023). The Langmuir isotherm model also frequently provides the best fit, suggesting monolayer adsorption onto a surface with a finite number of identical sites, further supporting the concept of specific, chemical interactions at homogeneous active sites (Mengistu et al., 2023; Anisuzzaman et al., 2023).

However, the predominant mechanism is rarely singular. A critical examination reveals that effective oil removal is typically a symphony of interactions. Physisorption via van der Waals forces and pore-filling plays a crucial role, especially in the initial rapid adsorption stage observed in many kinetics studies (Song & Tashmukhamed, 2025; Sun et al., 2023). Electrostatic attraction is pivotal for charged contaminants; for example, the adsorption of anionic surfactants like sodium dodecyl sulfate (SDS) is enhanced on positively charged biochar surfaces at low pH (Bautista Quispe et al., 2024). For non-polar oil fractions and aromatic compounds, π - π interactions between the carbon lattice of the AC and the aromatic rings of the pollutant are significant (Stavrinou et al., 2023). Hydrophobic interactions drive the adsorption of oil droplets and non-polar molecules away from the aqueous phase. The integration of these mechanisms is exemplified in composite adsorbents, where, for example, electrostatic attraction and hydrogen bonding were key for metal-paraben complexes (Nephphidi et al., 2025), and π - π stacking was dominant for dye removal (Sun et al., 2023).

This leads to a crucial kinetic insight: while PSO dominates, the intraparticle diffusion model often reveals multi-linear plots, indicating that film diffusion and intra-particle diffusion both influence the overall rate, especially in larger, real-world oil droplets or macromolecules (Khan et al., 2023; Mengistu et al., 2023). Therefore, the answer to SRQ2 is nuanced. The overarching kinetic model is PSO, pointing to chemisorption as a key endpoint, but the overall mechanism is multiplex, involving a sequence of physical diffusion steps followed by chemical binding at specific sites. The surface functional groups (e.g., $-\text{COOH}$, $-\text{OH}$) introduced during activation or via doping are not merely spectators; they are active participants that modulate these mechanisms by altering surface charge and providing specific binding sites (Ren et al., 2025; Azarshab et al., 2024).

Scalability, Regeneration, and Industrial Challenges (Addressing SRQ3)

Addressing SRQ3 uncovers the most significant gap between promising laboratory results and field-ready technology. The primary challenges for scaling up biomass-derived AC for industrial oil wastewater treatment are threefold: consistent precursor supply, efficient and cost-effective regeneration, and system integration/design. While laboratory studies often use idealized, single-contaminant synthetic wastewater, industrial effluents are complex matrices with fluctuating pH, salinity, and competing contaminants (e.g., heavy metals, other organics) that can foul or poison AC surfaces (Azarshab et al., 2024; Tran et al., 2024). Few studies in this review systematically tested their adsorbents in such real or simulated industrial wastewater, leaving a critical uncertainty about performance under realistic conditions.

Regeneration is the linchpin for economic viability. The literature shows that thermal regeneration, while common, is energy-intensive and can lead to significant capacity loss over multiple cycles due to pore collapse and chemical degradation of the carbon structure. For example, water hyacinth-derived AC for chromium removal saw efficiency drop from 93.25% to 21.35% after just seven cycles (Worku et al., 2023). Chemical regeneration with solvents or acids generates secondary waste streams. Emerging techniques like Cold Atmospheric Plasma (CAP) show promise, with one study reporting ~35% recovery of phenanthrene-loaded AC, but this is still low for industrial requirements (Stavrinou et al., 2023). Magnetic separation, as incorporated in Magnetic Activated Carbon (MAC), elegantly solves the solid-liquid separation problem—a major operational hurdle for powdered AC—and facilitates adsorbent recovery, though the regeneration of the spent MAC itself remains a challenge (Kusdarini et al., 2024; Yimin et al., 2025). The integration of adsorption into hybrid systems, such as electrocoagulation-adsorption sequences or constructed wetlands with AC pretreatment, presents a pragmatic opportunity. These systems can handle higher loads, improve overall removal efficiency (e.g., 66% COD removal in a sequential system), and potentially reduce the burden on the AC unit, extending its life (Sever et al., 2024; Abu-Dalo et al., 2024).

Therefore, the opportunities lie in designing for the lifecycle. Future research must pivot from just reporting maximum adsorption capacity (Q_{max}) to conducting comprehensive techno-economic analyses (TEA) and lifecycle assessments (LCA). This includes evaluating the energy and chemical inputs for activation, the longevity and regenerability of the adsorbent, and the fate of the spent material—whether it can be safely disposed of, used as a fuel source (as shown with cassava residue AC retaining 1601.23 kCal/kg), or even repurposed (e.g., dye-laden AC used as electrode material) (Khum-in et al., 2025; Khaophon et al., 2025). For practitioners, the choice of biomass-derived AC must move beyond adsorption capacity to consider the total cost of ownership, including pre-treatment needs, contact system design (batch vs. continuous column), separation method, and regeneration protocol.

Integrated Answer to the Primary Research Question and Concluding Synthesis

Synthesizing the findings from SRQs 1-3 provides a comprehensive, critical answer to the PRQ: Biomass-derived activated carbon is highly effective in removing oil and organic contaminants from wastewater in controlled laboratory settings, with performance primarily dictated by

synthesis-induced porosity/surface chemistry and governed by multiplex adsorption mechanisms. However, its real-world effectiveness and suitability for industrial application are contingent upon a complex interplay of factors beyond mere adsorption capacity, including precursor supply chain stability, resilient performance in complex matrices, and—most critically—a viable regeneration strategy that ensures economic and environmental sustainability.

The theoretical contribution of this body of work is the robust validation of chemical activation pathways and the pseudo-second-order/Langmuir framework for describing the adsorption process. The practical contribution is the demonstration that waste biomass can be transformed into a high-value material for environmental remediation, aligning with circular economy goals. However, the predominant limitation across the literature is the "batch study syndrome"—a focus on optimized, single-solute systems with little translation to continuous-flow, pilot-scale studies using real wastewater. This creates a valley of death between academic proof-of-concept and industrial adoption.

For practitioners, the application context is clear. Biomass-derived AC is a promising and often superior alternative to commercial AC for specific, well-defined wastewater streams, particularly where waste biomass is locally abundant and activation can be done cost-effectively. Initial pilot projects should focus on waste streams with relatively consistent composition. The selection of an adsorbent must be a systems-level decision, considering not just the adsorption isotherm but also the integration with upstream/downstream processes, the selected contactor (e.g., fixed-bed column with magnetic composites), and a planned end-of-life strategy for the spent material. Future research must prioritize long-term stability tests, regeneration cycle analysis with real effluents, and transparent techno-economic reporting to provide the data necessary for engineers and decision-makers to bridge the gap between laboratory potential and field-scale implementation.

CONCLUSION

This systematic review consolidates the frontier of knowledge on biomass-derived activated carbon (AC) for oil-contaminated wastewater remediation, offering a critical synthesis for both academic and industrial audiences. Our analysis confirms that biomass-derived AC is a technically potent and sustainable adsorbent, with chemical activation of diverse precursors—from agricultural residues to industrial sludges—consistently yielding high-surface-area materials capable of >90% contaminant removal in controlled settings. The adsorption process is dominantly governed by a multiplex mechanism initiating with physisorption and culminating in chemisorption, as robustly described by pseudo-second-order kinetics and Langmuir isotherm models.

The paramount contribution of this work lies in its dual focus: it not only validates the theoretical frameworks for adsorption but also rigorously maps the practical pathway from laboratory synthesis to field application. We identify the critical "valley of death" between high batch-mode efficacy and scalable, continuous industrial use, primarily stemming from regeneration challenges and performance degradation in complex matrices. For the practitioner,

the actionable insight is that material selection must evolve beyond maximizing adsorption capacity alone. Success hinges on adopting a systems-level design that integrates tailored AC synthesis (e.g., magnetic composites for separability) within hybrid treatment trains (e.g., coagulation-adsorption) and plans for the material's end-of-life, whether through innovative regeneration like cold atmospheric plasma or energy recovery.

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