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Comparative Synthesis of H_2SO_4-Activated Rice Straw and KOH-Activated Rice Husk Carbons: Evidence from Selected Wastewater Studies

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Abstract

Rice straw and rice husk are promising agricultural residues for producing activated carbon, but reported adsorption performance cannot be compared directly when precursor, activation chemistry, target contaminant, wastewater matrix, and operating conditions differ. This study qualitatively compares three selected experimental studies: H_2SO_4-activated rice straw carbon for Cr(VI) adsorption, KOH-activated rice husk carbon for tofu wastewater, and KOH-activated rice husk carbon for laundry and tofu wastewater. The synthesis compares precursor characteristics, activation conditions, adsorption or treatment conditions, reported performance, isotherm evidence, and potential treatment implications. The H_2SO_4-activated rice straw study reported an adsorption capacity (q_m) of 5.42 mg/g for Cr(VI) under its reported optimum conditions of pH 7, 100-mesh particle size, and 60 min contact time. The KOH-activated rice husk study for tofu wastewater reported reductions of 27% in Total Dissolved Solids (TDS) and 97% in Total Suspended Solids (TSS), while the comparative laundry/tofu study reported reductions of 82% COD, 27% TDS, and 97% TSS in laundry wastewater and 92% COD, 51% TDS, and 90% TSS in tofu wastewater. These findings are reported within their respective experimental contexts and are not treated as directly comparable performance scores. The synthesis indicates that adsorption behavior is associated with the combined effects of precursor, activation chemistry, pollutant or wastewater characteristics, and operating conditions. The study therefore provides a preliminary comparative framework and identifies the need for standardized experiments to evaluate precursor and activation effects independently.

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INTRODUCTION

Water pollution caused by industrial and domestic wastewater has become one of the most pressing environmental challenges worldwide. Rapid industrialization, urbanization, and the continuous expansion of small- and medium-scale industries have significantly increased the

discharge of untreated wastewater into aquatic environments (du Plessis, 2022; Singh et al., 2023). Industrial effluents commonly contain hazardous heavy metals, while domestic and agro-industrial wastewater is dominated by organic compounds, surfactants, suspended solids, and dissolved solids that contribute to deteriorating water quality and ecological imbalance (Kato & Kansha, 2024; Oladimeji et al., 2024; Zhang et al., 2023). Because of its high toxicity, carcinogenicity, mobility, and persistence in aquatic systems, one of the most dangerous heavy metal pollutants is hexavalent chromium (Cr(VI)) (Sutama et al., 2026). On the other hand, wastewater from tofu production and household laundry has high levels of Chemical Oxygen Demand (COD), Total Dissolved Solids (TDS), and Total Suspended Solids (TSS), which lower dissolved oxygen levels and endanger aquatic life if released untreated. As a result, creating wastewater treatment technologies that are effective, affordable, and environmentally sustainable has emerged as a top research priority (Sutama et al., 2025a, 2025b).

Adsorption has drawn a lot of interest among the existing treatment technologies because to its ease of use, high removal efficiency, cheap operating costs, and little secondary contamination (Ahmed Alsharif, 2025; Satyam & Patra, 2024). Because of its numerous active sites and well-developed porous structure, activated carbon is still one of the best adsorbents. However, because creating commercial activated carbon is expensive, researchers are investigating renewable biomass as a substitute precursor. Agricultural residues are particularly attractive because they are inexpensive, readily available, renewable, and simultaneously support waste valorization within a circular economy framework (Bandani et al., 2026; Gayathiri et al., 2022; Y. Wang et al., 2020). Rice-derived biomass, especially rice straw and rice husk, has attracted increasing interest owing to its high carbon content, lignocellulosic composition, and favorable physicochemical properties for activated carbon production. These characteristics enable rice biomass to be converted into efficient adsorbents through appropriate physical or chemical activation processes (Goodman, 2020; Islam et al., 2024; Kordi et al., 2024).

Activated carbon made from rice biomass has shown promising potential for wastewater treatment, but the available evidence comes from experimental studies with different precursor materials, activating agents, pollutants, and operating conditions. Three primary studies are particularly relevant to the present synthesis. Sutama et al., 2026 investigated H_2SO_4-activated rice straw carbon for Cr(VI) adsorption. In a separate study, Sutama et al. (2025a) investigated KOH-activated rice husk carbon for tofu wastewater treatment. Meanwhile, Sutama et al. (2025b) evaluated KOH-activated rice husk carbon for the treatment of both laundry and tofu wastewater. Although these studies provide useful evidence on the application of rice biomass-derived activated carbon, they represent different experimental systems and should therefore be interpreted within their respective contexts.

The main research gap is not simply the limited number of studies, but the difficulty of making a direct comparison across these heterogeneous experimental systems. The studies differ in biomass precursor, activating agent, target pollutant or wastewater matrix, adsorption conditions, and reported performance indicators. More importantly, the effects of biomass precursor and activating agent are confounded because the precursor and activation chemistry change simultaneously between the H_2SO_4-activated rice straw system and the KOH-activated rice husk systems. Consequently, differences in adsorption performance cannot be attributed exclusively to the activating agent. The available studies therefore cannot independently establish whether an observed difference arises from the intrinsic characteristics of rice straw versus rice husk, from H_2SO_4 versus KOH activation, or from the interaction of these factors with pollutant and operating conditions (Kumar Mishra et al., 2024; Xie et al., 2025).

This limitation indicates the need for a comparative synthesis that does not treat the reported adsorption performance as directly equivalent or as evidence of the superiority of one activation method over another. Instead, the comparison should identify patterns across the three

source studies while explicitly recognizing differences in precursor, activation chemistry, wastewater characteristics, and experimental conditions. Such an approach can clarify what conclusions are supported by the existing evidence and identify the experimental controls required to independently evaluate the effects of precursor and activating agent (Akhtar et al., 2025; W. Wang & Wang, 2022).

Therefore, this study presents a qualitative comparative literature synthesis of three selected primary experimental studies: Sutama et al. (2026), which examined H_2SO_4-activated rice straw carbon for Cr(VI) adsorption; Sutama et al. (2025a), which examined KOH-activated rice husk carbon for tofu wastewater; and Sutama et al. (2025b), which examined KOH-activated rice husk carbon for laundry and tofu wastewater. The synthesis compares precursor characteristics, activation conditions, physicochemical properties, adsorption or treatment conditions, reported performance, and adsorption isotherm evidence. Particular attention is given to the methodological heterogeneity among the studies and to the confounding of precursor and activating-agent effects. The objective is not to rank the activation methods, but to establish a context-sensitive comparison of the available evidence and to identify the limitations that must be addressed through standardized experiments in which precursor and activating agent can be evaluated independently.

METHODS

This study employed a qualitative comparative literature synthesis based on three selected primary experimental studies on rice biomass-derived activated carbon. The studies comprised Sutama et al. (2026) , which investigated H_2SO_4-activated rice straw carbon for Cr(VI) adsorption; Sutama et al. (2025a), which investigated KOH-activated rice husk carbon for tofu wastewater treatment; and Sutama et al. (2025b), which investigated KOH-activated rice husk carbon for laundry and tofu wastewater treatment. The synthesis compared precursor characteristics, activating agents, experimental conditions, physicochemical properties, and reported treatment performance within the original context of each study.

The three studies were selected because they directly examined rice biomass-derived activated carbon produced using chemical activation and reported quantitative adsorption or wastewater-treatment results. Eligible studies were required to provide information on the biomass precursor, activating agent, target pollutant or wastewater matrix, and relevant experimental conditions. Sutama et al. (2025a) and Sutama et al. (2025b), were treated as separate primary studies because they represented different experimental scopes, although both used KOH-activated rice husk carbon.

Data extracted from each study included biomass precursor, activating agent, activation conditions, target pollutant or wastewater type, adsorption conditions, reported adsorption capacity or removal efficiency, and adsorption isotherm results. The extracted information was organized into comparative tables and interpreted using qualitative content analysis and descriptive comparison. The analysis focused on identifying similarities and differences while considering the effects of precursor characteristics, activation chemistry, pollutant characteristics, and operating conditions (Gayathiri et al., 2022; Putri et al., 2026).

Table 1. Characteristics and Extracted Data of the Three Primary Studies

Study	Biomass precursor	Activating agent	Target pollutant/wastewater	Adsorption/treatment system	Key operating conditions	Main reported outcome	Isotherm evidence
Sutama et al. (2026)	Rice straw	H_2SO_4	Cr(VI)	Batch adsorption	pH 7; particle size 100 mesh; contact	q_m = 5.42 mg/g	Langmuir; R^2 = 0.8923

Study	Biomass precursor	Activating agent	Target pollutant/wastewater	Adsorption/treatment system	Key operating conditions	Main reported outcome	Isotherm evidence
					time 60 min		
Sutama et al. (2025a)	Rice husk	KOH	Tofu wastewater	Batch adsorption	Contact time up to 120 min; other conditions as reported in the source study	TDS reduction 27%; TSS reduction 97%	Langmuir and Freundlich models reported; both $R^2 > 0.90$
Sutama et al. (2025b)	Rice husk	KOH	Laundry and tofu wastewater	Batch adsorption	Optimum conditions reported separately for the wastewater matrices	Laundry: COD 82%, TDS 27%, TSS 97%; Tofu: COD 92%, TDS 51%, TSS 90%	Langmuir; $R^2 > 0.90$

Methodological heterogeneity was assessed based on differences in precursor biomass, activating agent, target pollutant or wastewater matrix, operating conditions, and reported response variables. An important limitation is that precursor type and activating agent were not varied independently among the source studies. The H_2SO_4-activated system used rice straw, whereas the KOH-activated systems used rice husk. Therefore, differences in reported performance cannot be attributed exclusively to the activating agent because the effects of precursor and activating agent are confounded (Satyam & Patra, 2024; Tetteh et al., 2024).

A meta-analysis or statistical pooling was not performed because the three studies differed substantially in experimental systems, target pollutants, wastewater matrices, operating conditions, and outcome measures. In addition, the studies did not provide a sufficiently consistent common effect-size metric and associated variance estimates required for meaningful statistical pooling. Therefore, the results were synthesized qualitatively and reported descriptively rather than statistically pooled or ranked.

Importantly, adsorption capacity (q_m, mg/g) and removal efficiency (%) were not directly compared as equivalent performance indicators. Adsorption capacity represents the amount of pollutant adsorbed per unit mass of adsorbent, whereas removal efficiency represents the percentage reduction in pollutant concentration. Both metrics are influenced by different experimental factors, including initial concentration, solution volume, adsorbent dose, and operating conditions. Consequently, the reported q_m and removal efficiency values were retained in their original forms and interpreted within their respective experimental contexts.

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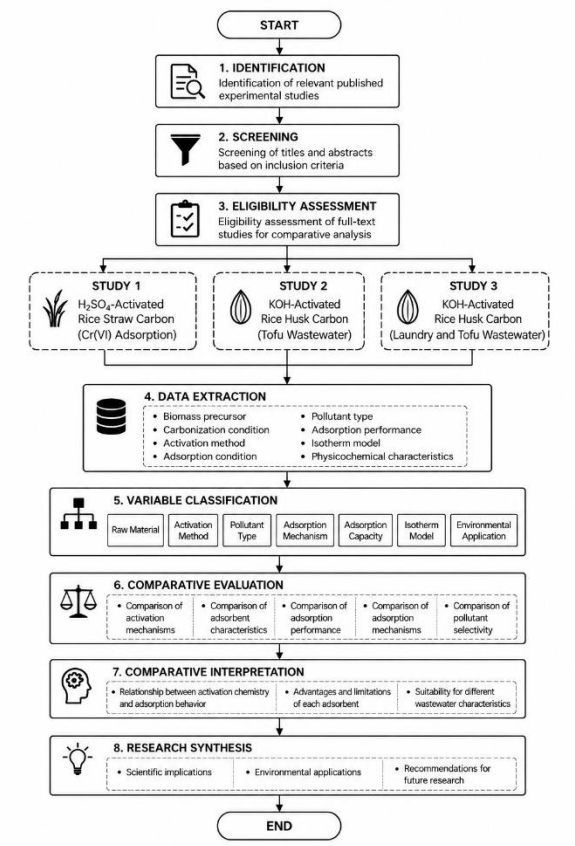


Figure 1. Research Workflow for Comparative Synthesis of Selected Activated Carbon Studies

RESULTS AND DISCUSSION

Comparative Activated Carbon Physicochemical Properties

The adsorption performance of activated carbon is influenced by its physicochemical characteristics, including surface functional groups, pore structure, and surface area. Across the three selected studies, differences in precursor and activation chemistry were associated with differences in the reported adsorption characteristics (Bosacka et al., 2022). H_2SO_4-activated rice straw carbon was associated with oxygen-containing surface functional groups, whereas KOH-activated rice husk carbon was associated with pore development and surface-area characteristics characteristics (Beshir et al., 2026). However, these differences cannot be attributed exclusively to the activating agents because the biomass precursors also differed. The experimental characteristics of the three selected studies are summarized in Table 2.

Table 2. Comparative Experimental Characteristics of the Selected Activated Carbon Systems

Parameter	Sutama et al. (2026)	Sutama et al. (2025a)	Sutama et al. (2025b)
Biomass precursor	Rice straw	Rice husk	Rice husk
Activating agent	Sulfuric acid (H_2SO_4)	Potassium hydroxide (KOH)	Potassium hydroxide (KOH)
Activation type	Chemical activation	Chemical activation	Chemical activation
Target system	Cr(VI) solution	Tofu wastewater	Laundry and tofu wastewater
Adsorption system	Batch	Batch	Batch
Optimum pH	7	As reported in source study	As reported in source study
Optimum contact time	60 min	120 min	90-120 min

Parameter	Sutama et al. (2026)	Sutama et al. (2025a)	Sutama et al. (2025b)
Particle size	100 mesh	As reported in source study	Not specifically reported
Adsorbent dose	As reported in source study	As reported in source study	As reported in source study
Main analytical parameters	Cr(VI) concentration	COD, TDS, TSS	COD, TDS, TSS

The comparison shows that the three studies employed different biomass precursors, activating agents, and treatment systems (Li et al., 2024; Y. Liu et al., 2024). The H_2SO_4-activated carbon was derived from rice straw and applied to Cr(VI) adsorption, whereas the KOH-activated carbon was derived from rice husk and applied to tofu and laundry wastewater treatment. These differences indicate that precursor type and activating agent are confounded among the studies, and therefore their individual effects cannot be separated based on the available experimental evidence (Karaer Yağmur, 2026; Kuyucu et al., 2026).

Comparative Adsorption Performance

The reported adsorption and treatment performance differed across the selected experimental systems and should be interpreted within their respective conditions. At pH 7, a particle size of 100 mesh, and a contact time of 60 min, the H_2SO_4-activated rice straw study reported a maximum Cr(VI) adsorption capacity of 5.42 mg/g and a Langmuir model fit of R^2 = 0.8923. This R^2 value indicates a reasonable fit to the Langmuir model, but it is not sufficient on its own to establish Langmuir as the superior isotherm model or to confirm monolayer adsorption. For the KOH-activated rice husk tofu wastewater study, Sutama et al. (2025a) reported both Langmuir and Freundlich models with $R^2 > 0.90$, indicating that both models provided reasonable fits to the experimental data. Sutama et al. (2025b) also reported a Langmuir model with $R^2 > 0.90$; however, this value should likewise be interpreted as model-fit evidence rather than definitive evidence of model superiority. Therefore, the present synthesis does not designate Langmuir or Freundlich as a universally superior model, and the isotherm results are interpreted within the experimental context of each source study.

Table 3. Reported Adsorption and Wastewater Treatment Performance

Study	Target pollutant / parameter	Performance indicator	Reported result	Interpretation within source-study context
Sutama et al. (2026)	Cr(VI)	Maximum adsorption capacity (q_m)	5.42 mg/g	Reported maximum adsorption capacity under the study's optimum conditions
Sutama et al. (2025a)	TDS	Removal efficiency	27%	Reduction reported for tofu wastewater
Sutama et al. (2025a)	TSS	Removal efficiency	97%	Reduction reported for tofu wastewater
Sutama et al. (2025b)	COD – laundry wastewater	Removal efficiency	82%	Reduction reported for laundry wastewater
Sutama et al. (2025b)	TDS – laundry wastewater	Removal efficiency	27%	Reduction reported for laundry wastewater
Sutama et al. (2025b)	TSS – laundry wastewater	Removal efficiency	97%	Reduction reported for laundry wastewater
Sutama et al. (2025b)	COD – tofu wastewater	Removal efficiency	92%	Reduction reported for tofu wastewater
Sutama et al. (2025b)	TDS – tofu wastewater	Removal efficiency	51%	Reduction reported for tofu wastewater

Study	Target pollutant / parameter	Performance indicator	Reported result	Interpretation within source-study context
Sutama et al. (2025b)	TSS – tofu wastewater	Removal efficiency	90%	Reduction reported for tofu wastewater

The reported outcomes should be interpreted within the experimental context of each source study. The Cr(VI) study reported adsorption capacity (q_m) in mg/g, whereas the wastewater studies primarily reported removal efficiencies (%) for COD, TDS, and TSS. These indicators represent different aspects of treatment performance and are not directly interchangeable. Therefore, the numerical values in Table 3 are presented as reported by the respective source studies and are used for contextual comparison rather than direct performance ranking (Beshir et al., 2026; Malouchi et al., 2026).

The comparison also indicates substantial heterogeneity among the three studies. The Cr(VI) system involved a defined aqueous pollutant solution, whereas the laundry and tofu studies involved complex wastewater matrices containing multiple water-quality parameters. Consequently, differences in reported performance may reflect not only the precursor and activating agent but also pollutant characteristics, wastewater composition, and operating conditions. The results therefore do not support attributing performance differences solely to H_2SO_4 or KOH activation.

Effect of Chemical Activation on Adsorption Mechanism

The comparative evidence suggests that chemical activation may influence the surface characteristics and adsorption behavior of rice biomass-derived activated carbon. However, the available studies do not allow the independent effect of activation chemistry to be separated from the effect of biomass precursor. The H_2SO_4-activated system was produced from rice straw, whereas the KOH-activated systems were produced from rice husk. Therefore, the observed differences in adsorption behavior may reflect the combined effects of precursor characteristics, activation chemistry, pollutant properties, and operating conditions rather than the activating agent alone (Shahcheragh et al., 2023).

From a conceptual perspective, H_2SO_4 activation may contribute to changes in oxygen-containing surface functional groups, while KOH activation may promote pore development and changes in surface area. These characteristics can influence interactions between the adsorbent and target pollutants. Nevertheless, these interpretations should be considered as literature-based conceptual explanations rather than direct evidence of causality in the present synthesis, because the precursor and activating agent were not independently varied in the selected studies.

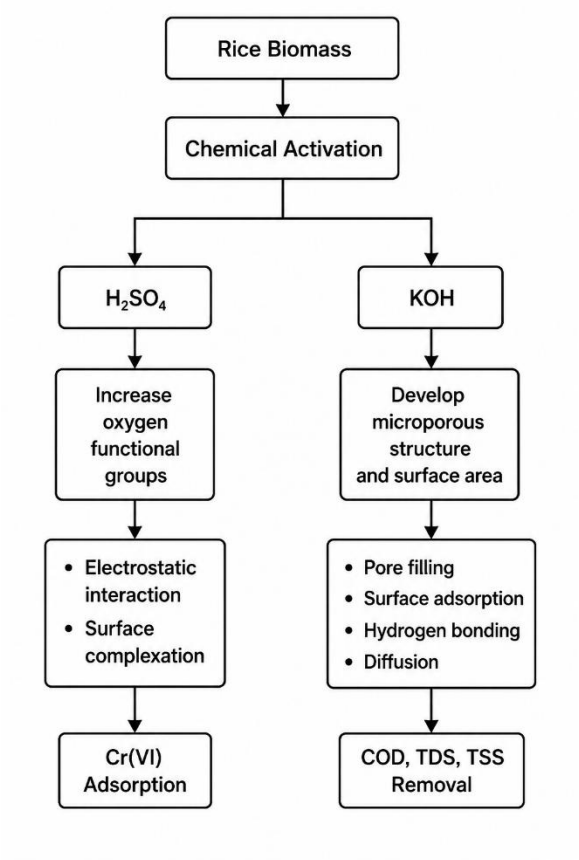


Figure 2. Conceptual Representation of Possible Adsorption Mechanisms of Rice Biomass-Derived Activated Carbon

H_2SO_4 activation may contribute to changes in oxygen-containing functional groups, while KOH activation may promote pore development and changes in surface area. These characteristics may influence interactions between the adsorbent and target pollutants (Li et al., 2024). However, the available studies do not allow these effects to be attributed exclusively to the activating agents because the biomass precursors also differed. Therefore, the proposed mechanisms should be regarded as conceptual interpretations based on the reported characteristics and relevant adsorption literature rather than as experimentally verified causal mechanisms in the present synthesis (C. Liu et al., 2025) .

The comparison suggests that adsorption behavior may result from the combined effects of biomass precursor, activation chemistry, pollutant characteristics, and operating conditions. Therefore, neither precursor type nor activation chemistry can be considered independently as the primary determinant of adsorption performance based on the selected studies. Standardized experiments in which precursor and activating agent are independently varied are required to clarify their individual and interactive effects.

Proposed Adsorbent Selection Framework for Wastewater Treatment

The comparative evidence suggests that wastewater characteristics should be considered together with the physicochemical characteristics of the selected adsorbent when designing a treatment strategy. For wastewater containing dissolved heavy metals, surface functional groups may play an important role in adsorption interactions, whereas wastewater containing organic pollutants and suspended solids may require adsorbents with appropriate pore structure and surface characteristics. However, the selected studies do not provide sufficient evidence to attribute these characteristics exclusively to H_2SO_4 or KOH activation because different biomass precursors were also used (Fouda-Mbanga et al., 2024).

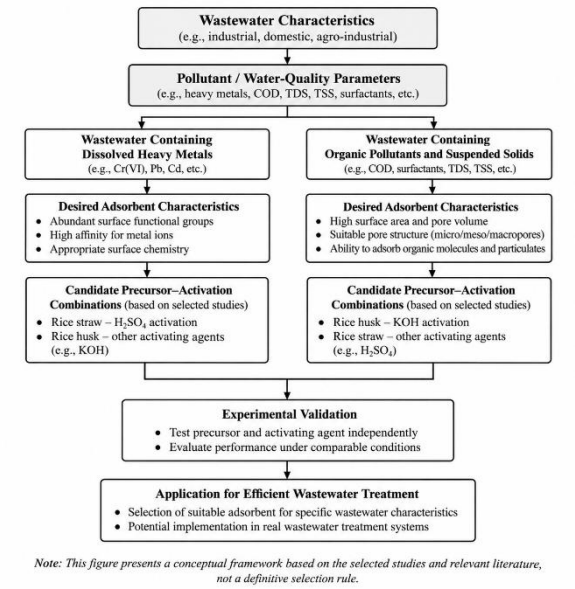


Figure 3. Conceptual Framework for Selecting Rice Biomass-Derived Activated Carbon Based on Wastewater Characteristics

The proposed framework highlights that adsorbent selection should consider both biomass precursor and activation chemistry in relation to the characteristics of the target pollutant or wastewater. The available studies suggest that different precursor–activation combinations may produce adsorbents with different physicochemical characteristics and treatment behaviors. However, because the selected studies did not independently vary precursor and activating agent, the framework should be regarded as a preliminary conceptual guide rather than a validated rule for selecting a specific activation method. Standardized experiments are required to determine the independent and interactive effects of precursor and activation chemistry.

Environmental Implications and Future Perspectives

The comparative findings demonstrate that rice biomass-derived activated carbon represents a sustainable alternative to commercial adsorbents for wastewater treatment. In addition to enhancing wastewater remediation, the use of rice straw and rice husk encourages the value-adding of agricultural leftovers, promoting the circular economy's tenets and lessening the environmental effects of biomass disposal. Matching adsorbent characteristics with wastewater parameters may help guide treatment design; however, this relationship requires validation under standardized experimental conditions (Alam et al., 2020; Goodman, 2020).

Future studies should validate the proposed adsorbent selection framework under standardized experimental conditions involving different wastewater types and activation parameters. Additional investigations on adsorbent regeneration, continuous fixed-bed adsorption systems, and techno-economic feasibility are also recommended to support the large-scale application of rice biomass-derived activated carbon for sustainable wastewater treatment

CONCLUSION

This comparative synthesis demonstrates that rice straw- and rice husk-derived activated carbons show potential for different wastewater treatment applications; however, the available evidence does not allow the independent contribution of biomass precursor and activating agent to be established. The three selected studies differed in precursor type, activation chemistry, target pollutant or wastewater matrix, and operating conditions. In particular, the H_2SO_4-activated system used rice straw, whereas the KOH-activated systems used rice husk. Therefore,

differences in reported adsorption or removal performance should not be attributed solely to the activating agent.

The reported isotherm results provide evidence of model fit within the respective experimental systems, but they do not establish a universally superior adsorption model or a single dominant adsorption mechanism. Similarly, the reported adsorption capacity and removal efficiency values represent different performance indicators and should be interpreted within their original experimental contexts rather than used to rank the adsorbents directly.

The comparative analysis therefore provides a preliminary framework for understanding the combined influence of biomass precursor, activation chemistry, pollutant characteristics, and operating conditions on adsorption behavior. Future studies should employ standardized experimental designs in which precursor type and activating agent are varied independently, preferably under comparable adsorption conditions, to distinguish their individual and interactive effects. Such experiments are necessary to validate the proposed framework and establish a more robust basis for selecting rice biomass-derived activated carbon for specific wastewater treatment applications.

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