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Data-Driven Optimization of Agricultural Waste Adsorbents: Statistical Insights on Wastewater Treatment Efficiency

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ABSTRACT

Water pollution poses a significant global challenge, threatening human health, ecosystems, and environmental sustainability. Conventional wastewater treatment methods often fall short in addressing emerging contaminants, necessitating innovative and cost-effective alternatives. This study evaluates the potential of agricultural by-products, rice husks and coffee husks, converted into activated carbon (AC) through carbonization (300°C and 400°C, respectively), and followed by physical and ZnCl₂-assisted chemical activation, as sustainable adsorbents for wastewater treatment. Raw wastewater samples were collected from the Kigongi Sewage Treatment Plant in Kabale, Uganda, and analyzed for turbidity, pH, *Escherichia coli*, total suspended solids (TSS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD). Jar tests established optimal dosages of 70 mg/L for rice husk-activated carbon (RHAC) and 80 mg/L for coffee husk-activated carbon (CHAC) supported by regression modeling. Under these conditions, RHAC achieved 64.3% turbidity and 84.4% TSS removal, while CHAC removed 60.7% turbidity and 72.9% TSS. In terms of microbial contamination, RHAC and CHAC achieved 59.18% and 34.69% removal of *Escherichia coli*, respectively, indicating meaningful antimicrobial activity in real sewage wastewater. Analysis of variance (ANOVA) results confirmed the statistical significance of RHAC's superior performance in reducing BOD and COD, and regression analysis demonstrated strong correlations between adsorbent dosage and pollutant removal efficiencies. These findings illustrate the viability of agricultural-waste-derived ACs as low-cost and sustainable polishing agents for wastewater treatment. Beyond addressing immediate pollutant loads, their deployment advances circular economy goals and environmental conservation by transforming biomass residues into value-added materials. Future research should examine regeneration capacity and performance against emerging contaminants to further validate their scalability under real-world conditions.

1 | Introduction

Water contamination remains one of the most critical environmental issues worldwide, with far-reaching impacts on public

health and ecological stability. Polluted water bodies often harbor pathogenic microorganisms and hazardous chemicals that contribute to widespread illnesses such as cholera, dysentery,

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and even long-term conditions including cancer [1, 2]. In addition to these health concerns, aquatic ecosystems are severely affected by pollutants that alter species diversity, destabilize food webs, and degrade natural habitats [3]. Although significant progress has been made in advancing pollution control measures, the continuous discharge of contaminants highlights the urgent need for more resilient, sustainable, and affordable water treatment solutions [4].

Human activities remain the dominant drivers of water pollution, with untreated domestic sewage, industrial discharges, agricultural runoff, and accidental oil releases recognized as the most critical sources [5]. The influx of these pollutants into natural water bodies initiates severe ecological disturbances, most notably eutrophication, which lowers dissolved oxygen levels and promotes harmful algal blooms that threaten aquatic life and amplify the risks of waterborne disease outbreaks [6]. Rapid industrial growth and urban expansion have further aggravated the situation, resulting in wastewater streams enriched with heavy metals, persistent organic compounds, and excessive nutrient loads. These contaminants not only compromise water quality but also heighten public health risks, contributing to long-term ecological degradation [7, 8].

Wastewater treatment is essential for sustainable development, yet conventional processes such as sedimentation, chemical oxidation, and biological methods, while effective in lowering pollutant loads, face key drawbacks including high energy demands, chemical dependence, and sludge generation [8, 9]. More critically, these systems are often ineffective against emerging contaminants such as pharmaceuticals and pesticides, which persist in treated effluents, underscoring the need for innovative, cost-effective, and sustainable alternatives [10].

In Uganda and many parts of East Africa, over 80% of domestic wastewater and fecal sludge are inadequately treated or directly discharged into the environment [11]. Urban informal settlements and small towns face particularly acute challenges due to limited infrastructure, poor planning, and insufficient operational funding [12]. These realities necessitate cost-effective, decentralized wastewater treatment options that are suitable for localized deployment. Rice husk and coffee husk were selected as bio-adsorbents due to their high availability in southwestern Uganda and their proven potential in recent studies as precursors for activated carbon (AC) production [13]. Their conversion into AC supports both pollution reduction and circular economy goals.

While previous studies on RHAC and CHAC primarily relied on synthetic or controlled wastewater tests [14–16], this study is distinctive by integrating real effluent samples from the Kigongi Sewage Treatment Plant with optimization via analysis of variance (ANOVA) and regression modeling. This combined field-laboratory framework remains underexplored in current literature and offers more transferable results for real-world applications. Adsorption is a proven and widely applied method for wastewater purification, with AC being highly effective for removing organic and inorganic contaminants [17, 18]. Agricultural by-products such as rice husks and coffee husks have recently emerged as sustainable, low-cost precursors for AC production. Their unique physicochemical composition, silica-rich rice husks and lignocellulosic coffee husks, enhances adsorption performance while contributing to waste valorization and circular economy goals [19].

The transformation of agricultural residues into AC provides dual benefits: improved wastewater treatment efficiency and reduced environmental impacts from waste disposal [20]. This process not only prevents greenhouse gas emissions from biomass decomposition but also enhances resource utilization by generating high-value adsorbents. Innovative treatment technologies such as microbial fuel cells, graphene-based materials, algal remediation, and constructed wetlands have also been explored [21, 22]. While effective in controlled settings, their large-scale application is limited by high costs, energy requirements, and technical complexity. In contrast, ACs derived from rice husks and coffee husks present a cost-effective and accessible option. They provide high pollutant removal efficiency while promoting circular economy goals. Such practical advantages make them particularly suited for adoption in low- and middle-income regions where affordable wastewater treatment is urgently needed.

The adsorption efficiency of AC in wastewater treatment is closely linked to its physicochemical characteristics, which are largely governed by the activation method employed. Two major approaches are commonly applied: physical and chemical activation. In physical activation, the raw precursor is first carbonized in an inert environment and then exposed to activating gases such as steam or carbon dioxide, a process that primarily increases surface porosity and overall surface area [23]. Chemical activation, by contrast, relies on chemical reagents such as zinc chloride ($ZnCl_2$) or potassium hydroxide (KOH), which facilitates the development of a more extensive pore network and a larger surface area. This method often produces ACs with enhanced structural properties, resulting in superior adsorption capacity compared to physically ACs [24, 25].

Rice husk-derived activated carbon (RHAC) possesses unique physicochemical attributes that make it particularly suitable for wastewater remediation. RHAC typically contains a high proportion of mesopores, which enables effective adsorption of larger organic molecules and complex pollutants commonly found in sewage effluents [26]. When subjected to chemical activation, its surface area and pore structure are further optimized, resulting in enhanced pollutant removal efficiency, especially for turbidity and nutrient reduction [27]. Likewise, coffee husk-derived activated carbon (CHAC) has demonstrated strong adsorption potential, primarily due to the abundance of oxygen-containing functional groups such as phenolic and carboxylic moieties. These groups play a critical role in binding organic contaminants and heavy metals, thereby broadening its applicability for diverse wastewater contaminants [28]. The adsorption efficiency of both RHAC and CHAC is therefore strongly influenced by their pore size distribution, activation route, and the characteristics of target pollutants.

Recent studies in Table 1 applied RHAC and CHAC to pollutants such as dyes, heavy metals, pharmaceuticals, and municipal wastewater organics. However, most were conducted under synthetic conditions, with limited pollutant coverage and minimal statistical validation. The novelty of the present study lies in its integration of ANOVA and regression-based optimization with field-based sewage wastewater characterization, covering a wider pollutant spectrum, including microbial contaminants. This combination provides a more robust and operationally relevant framework for evaluating low-cost adsorbents in real wastewater contexts.

TABLE 1 | Comparison with recent literature on RHAC/CHAC for wastewater treatment.

Study (year)	Precursor	Activation/prep	Water matrix	Primary targets	Optimal conditions	Performance	Regeneration
Mortada et al. (2023) [29]	Rice husk activated carbon (RHAC)	Chemical activation with ZnCl_2 ; $\text{S_BET} \approx 813.5 \text{ m}^2/\text{g}$	Municipal wastewater (COD removal)	COD	pH 3.0; dose 0.1 g/L; contact 100 min; 25°C – 50°C	97.0% COD removal at 25°C (drops to 74.5% at 50°C); Langmuir $q_{\text{max}} \approx 45.9 \text{ mg/g}$	Exothermic adsorption; H4 hysteresis (mesoporosity)
Negm et al. (2024) [30]	RHAC modified with Ni/Al-LDH composite	RHAC + co-precipitated Ni/Al-LDH (composite)	Industrial wastewater (Pb^{2+})	Pb^{2+}	pH 7; 210 min; $\text{C}_0 = 50 \text{ mg/L}$	82% Pb^{2+} removal (50 mg/L) in 210 min; Freundlich isotherm; PSO kinetics	Synergistic complexation/ion-exchange
Castro et al. (2023) [28]	Coffee husk activated carbon (CHAC)	Chemical activation: H_3PO_4 and ZnCl_2 variants; $\text{S_BET} (\text{H}_3\text{PO}_4) \approx 430 \text{ m}^2/\text{g}$	Synthetic dye effluent (Ponceau 4R)	Ponceau 4R dye	$\approx 2 \text{ g/L}$; 60–90 min (equilibrium $\approx 60 \text{ min}$ for some runs)	Up to $\approx 100\%$ dye removal under optimized H_3PO_4 -AC conditions; $q_{\text{e}} \approx 9.9 \text{ mg/g}$	Elovich/PFO/PSO tested; Langmuir fit for equilibrium
Aragaw et al. (2022) [31]	Activated coffee husk carbon	Chemical activation (details in paper)	Electroplating wastewater (Cr)	Cr (total/Cr[VI])	Reported in paper (batch optimization)	Effective Cr removal; isotherm + kinetics modeled; desorption studied	Desorption and reusability evaluated
Tadess et al. (2025) [32]	Coffee husk AC + bentonite composite	CHAC (chemical activation) blended with bentonite	Real tannery wastewater (Ethiopia)	TDS, Cl^- (and others)	Composite-optimized (see paper)	TDS $\downarrow 90.7\%$, $\text{Cl}^- \downarrow 83.6\%$ under optimized conditions	Composite approach enhances performance vs. CHAC alone
Demirdağ et al. (2025) [33]	RHAC (KOH activation; high surface area)	KOH activation; high-surface-area RHAC	Synthetic pharmaceutical solution	Ciprofloxacin (CIP)	Batch: pH, dose, contact time optimized (see paper)	High CIP uptake; isotherms/kinetics/thermodynamics evaluated	Designed as scalable, low-cost route
Kaya et al. (2024) [34]	RHAC	H_3PO_4	Environmental (mixed pollutants)	Heavy metals (Pb^{2+} , Cd^{2+} , Cu^{2+} , Zn^{2+})	pH 6–7; adsorbent dose 0.5–1.0 g/L; contact time $\approx 120 \text{ min}$	Described adsorption efficiencies	Nil

This study examines the adsorption efficiency of AC derived from rice and coffee husks in removing pollutants from wastewater, offering data-driven insights into their potential as sustainable alternatives for wastewater treatment. The research assesses their performance at the Kigongi Sewage Treatment Plant to determine the most effective option for optimizing treatment outcomes. The findings contribute to ongoing efforts to develop low-cost, eco-friendly solutions that enhance water quality while promoting sustainable waste management practices.

2 | Methods

2.1 | Materials Preparation

The preparation of materials for wastewater treatment involved sourcing, cleaning, drying, and carbonizing agricultural residues to enhance their adsorption efficiency. Rice and coffee husks were obtained from local agricultural mills in Kayunga District, Uganda. These raw materials were transported in clean polythene bags to the Ministry of Public Service laboratories in Wandegaya for further preparation and analysis. The raw rice and coffee husks were thoroughly washed with distilled water to remove dirt and impurities. The cleaned husks were then oven-dried at 60°C until completely dehydrated to ensure uniformity in moisture content before carbonization. Approximately 1 kg of each pretreated sample was weighed and placed in an electric furnace (Model: SHTL-233).

The furnace was heated to 300°C for rice husks and 400°C for coffee husks. These specific temperatures were selected based on prior optimization studies. For rice husk, effective carbonization typically occurs between 400 and 600°C, enhancing pore development without excessive ash formation [35]. Coffee husk benefits from carbonization at higher temperatures (~400°C) to improve volatile release and surface reactivity. The carbonization process lasted for 2 h, after which the furnace was allowed to cool before collecting the carbonized materials. The carbonized materials underwent further activation processes to enhance porosity and adsorption efficiency. Physical activation involved heating the carbonized biomass at 700°C for 1 h in a steam-nitrogen atmosphere. For chemical activation, the biomass was soaked in 40% H₃PO₄ for 12 h at room temperature, followed by heating at 450°C for 1 h in a muffle furnace.

2.2 | Data Collection

The wastewater samples were collected from the Kigongi Sewage Treatment Plant in Kabale, Uganda, a facility that serves as a hub for treating domestic wastewater from various sources, including kitchens, sinks, showers, laundry facilities, hospitals, and restaurants. Samples were gathered after the screening stage (primary treatment) and before entering the anaerobic pond. Raw wastewater was collected using a sterilized 5-L jerry can to ensure a sufficient volume for laboratory analyses. Sampling was conducted as grab samples during morning peak flow (between 9:00 a.m. and 10:00 a.m.) over three consecutive days to reduce variability. Samples were taken after screening (primary treatment) but before entering the anaerobic pond, allowing for characterization of high-strength influent with minimal treatment interference.

The collected samples were immediately transported to the National Water and Sewerage Corporation laboratory in Kabale for testing, adhering to standard procedures outlined in ISO 5667-10:1992 and Uganda National Environmental Standards. A jar test, also known as a flocculation test, was conducted to determine the optimal dosages of RHAC and CHAC for wastewater treatment. The jar test was conducted using a flocculation apparatus, with mixing conditions consisting of rapid mixing at 200 rpm for 2 min, followed by slow mixing at 30 rpm for 15 min, and a settling time of 30 min [36]. Raw wastewater samples were treated with varying dosages ranging from 40 to 90 mg/L of AC to assess their effectiveness in pollutant removal and adsorption capacity. Chemical oxygen demand (COD) in the sampled sewage effluent originates mainly from oxidizable organic matter, including proteins, carbohydrates, fats, and detergents derived from household activities, as well as a fraction of refractory organics such as hydrocarbons, pharmaceuticals, and industrial residues. This composition reflects the combined domestic and municipal sources contributing to sewage influent.

2.3 | Data Processing and Analysis

The following analyses were performed on both raw and treated wastewater. Biochemical oxygen demand (BOD) was measured using the azide modification of the Winkler method. The BOD samples were incubated at 20°C for 5 days in the dark, consistent with standard protocols (ISO 5815-1:2019). COD was determined using the spectrophotometric method. Total suspended solids (TSS) and total dissolved solids (TDS) were measured using standard gravimetric methods. pH and electrical conductivity (EC) were measured with a pH meter and conductivity meter, respectively. Ammonia, nitrogen, and total phosphates were determined using the Nessler reagent and the ammonium molybdate method. Sulfates and *E. coli* levels were quantified using sulfate reagent powder and microbiological tests. *E. coli* was quantified using the membrane filtration method with m-FC agar, incubated at 44.5°C for 24 h, following EPA Method 1603. The efficiency of RHAC and CHAC in reducing contaminants was calculated using Equation (1) as follows:

$$\text{Removal efficiency} = \frac{(C_{\text{initial}} - C_{\text{final}})}{C_{\text{initial}}} \times 100, \quad (1)$$

where C_{initial} and C_{final} are the contaminant concentrations before and after treatment, respectively. The results were statistically analyzed using Microsoft Excel. The data were presented in tabular and graphical formats to illustrate the performance of RHAC and CHAC, allowing for a comprehensive comparison with Uganda National Standards for effluent discharge. All tests were conducted in compliance with ISO 5667-10:1992 and Uganda National Environmental Standards. Reagents and equipment were calibrated to ensure accuracy and reliability. Each test was performed in triplicate, and average values were recorded to minimize experimental errors. All quantitative results are expressed as mean $\pm$ standard deviation, and statistical outputs were generated to reflect confidence levels in measured values. QA/QC protocols included reagent blanks, duplicate samples, and standard recovery checks to ensure analytical reliability.

TABLE 2 | Physicochemical parameters of raw wastewater.

Parameter	Units	Measured value	Permissible limit
Turbidity	NTU	140	300
TSS	mg/L	540	100
TDS	mg/L	780	1000
pH	—	7.8	6.0–8.0
EC	$\mu\text{S}/\text{cm}$	1327	1500

2.4 | Statistical Analysis

In order to comprehensively evaluate treatment efficiency, statistical tools such as ANOVA and regression analysis were employed. A one-way ANOVA was conducted to determine whether the differences in removal efficiencies between RHAC and CHAC were statistically significant across key water quality parameters. The ANOVA was conducted under a completely randomized design (CRD), with treatment type (RHAC vs. CHAC) as the grouping factor. A significance level of $p < 0.05$ was used to determine differences in treatment outcomes across pollutant types. Data from three experimental trials per parameter were analyzed, with ANOVA computing the Sum of Squares (SS), degrees of freedom (df), mean square (MS), F -statistic, and p -value. A significance threshold of 0.05 was applied to confirm statistical relevance. This analysis reinforced the reliability of findings by ensuring that observed differences in treatment performance were not due to random variation.

In order to further explore the relationships between treatment variables, regression analysis was utilized. The regression analysis was performed using Python's *statsmodels* library, and results were visually represented through scatter plots with fitted regression lines. Python v3.11 with *statsmodels* v0.14.0 was used. The OLS () function from *statsmodels.api* was applied to fit linear regression models. The analysis included regression coefficients, R^2 , and p -values, and the visualizations were presented using *matplotlib* and *seaborn*. Specifically, linear regression analysis was conducted to model the relationship between adsorbent dosage and removal efficiencies for key wastewater parameters, including turbidity, TSS, BOD, COD, pH, EC, and *E. coli*. In this analysis, the dosage of AC (RHAC and CHAC) served as the independent variable, while removal efficiencies were the dependent variables.

3 | Results and Discussion

3.1 | Physicochemical Parameters of Raw Wastewater

The raw wastewater sample collected from the Kigongi Sewage Treatment Plant exhibited notable physicochemical characteristics, as presented in Table 2. The turbidity was recorded at 140 NTU, which is within the permissible limit of 300 NTU set by Uganda's national effluent discharge standards. However, the TSS concentration was significantly elevated at 540 mg/L, far exceeding the allowable limit of 100 mg/L, indicating a substantial presence of particulate matter. The TDS measured 780 mg/L, remaining within the permissible threshold of 1000 mg/L, while the pH value of 7.8 indicated a neutral to slightly alkaline condition, compliant with the regulatory range of 6.0–8.0. Additionally, the EC of 1327 $\mu\text{S}/\text{cm}$

was below the maximum permissible limit of 1500 $\mu\text{S}/\text{cm}$, reflecting moderate ionic content in the wastewater.

3.2 | Biological Properties of Raw Wastewater

The biological analysis of the raw wastewater revealed a high concentration of *E. coli* at 490,000 CFU/100 mL, far exceeding the permissible limit of 5000 CFU/100 mL. This finding underscores significant microbial contamination and highlights the necessity for effective treatment to meet discharge standards. The BOD was recorded as 29.1 mg/L, indicating a considerable amount of biodegradable organic matter, while the COD was 660 mg/L, reflecting a high level of both organic and inorganic pollutants. These values emphasize the urgent need for efficient wastewater treatment processes to mitigate organic pollution and microbial risks.

3.3 | Optimizing RHAC and CHAC Dosages for Enhanced Supernatant and Filtrate Quality in Wastewater Treatment

The effectiveness of RHAC and CHAC in improving wastewater quality has been substantiated by various studies. RHAC has been shown to significantly reduce turbidity and TSS, achieving optimal performance at a dosage of 70 mg/L, which resulted in a turbidity of 70 NTU and TSS of 120 mg/L in the treated liquid, as indicated in Table 3. This performance is corroborated by findings that highlight the high adsorption capacity of AC derived from agricultural wastes, including rice husk, which is recognized for its porous structure and surface area that facilitate the removal of contaminants from water [37]. Furthermore, studies indicate that RHAC not only enhances water clarity but also effectively removes various pollutants, making it suitable for safe disposal or reuse [38, 39]. Maimulyanti et al. [40] stressed that RHAC is more effective for larger organic pollutants, while CHAC excels in removing smaller contaminants due to its microporous structure. These findings inform decisions on which precursor to use for optimal performance at the Kigongi Sewage Treatment Plant.

In comparison, CHAC demonstrated a higher optimal dosage requirement of 80 mg/L to achieve similar reductions in turbidity and TSS, yielding a turbidity of 75 NTU and TSS of 124 mg/L in the treated liquid, as indicated in Table 4. While slightly less efficient than RHAC, CHAC still shows significant potential for wastewater treatment. Research has indicated that AC from coffee husks possesses functional groups that enhance its adsorption capabilities, allowing it to effectively reduce impurities in wastewater [31, 41]. Moreover, the comparative studies on the adsorption efficiency of various agricultural waste-derived ACs suggest that while RHAC may have a slight edge in terms of dosage efficiency, CHAC remains a viable alternative for improving water quality [42].

3.4 | Comparative Treatment Efficiency of RHAC and CHAC

The performance efficiency of RHAC and CHAC was evaluated for various contaminants. The results are summarized in Table 5 and illustrated in Figure 1. The relationship between turbidity and TSS is well established, as TSS directly quantifies all suspended solids that significantly contribute to turbidity in water [43]. RHAC exhibits superior efficacy in reducing turbidity and TSS,

TABLE 3 | Effect of RHAC dosage on supernatant and filtrate water quality.

No/ jar	Dosage ×10 (mg/L)	Floc formation order	Floc size	Settlement order	Turbidity (NTU)	Color (PtCo)	pH	TDS (mg/L)	EC (μS/cm)	TSS (mg/L)
1	40	6	S	6	110	480	7.77	785	1200	230
2	50	5	M	5	104	476	7.76	781	1120	160
3	60	3	L	2	82	450	7.74	784	990	144
4	70	1	L	1	70	400	7.64	784	980	120
5	80	2	L	3	78	488	7.73	790	1100	133
6	90	4	V.L	4	85	530	7.65	800	1230	139
7	40	6	—	—	98	—	7.75	—	1000	120
8	50	5	—	—	77	—	7.75	—	980	110
9	60	3	—	—	64	—	7.70	—	770	98
10	70	1	—	—	50	—	7.62	—	740	84
11	80	2	—	—	59	—	7.71	—	1006	102
12	90	4	—	—	63	—	7.61	—	1020	119

TABLE 4 | Effect of CHAC dosage on supernatant and filtrate water quality.

No/ jar	Dosage ×10 (mg/L)	Floc formation order	Floc size	Settlement order	Turbidity (NTU)	Color (PtCo)	pH	TDS (mg/L)	EC (μS/cm)	TSS (mg/L)
1	40	5	M	5	105	468	7.79	782	1221	166
2	50	6	S	6	115	491	7.78	786	1130	235
3	60	4	VL	4	90	535	7.67	802	1235	140
4	70	2	L	3	80	489	7.74	795	985	134
5	80	1	L	1	75	410	7.66	785	991	124
6	90	3	L	2	85	453	7.75	784	1112	146
7	40	5	—	—	80	—	7.77	—	1102	123
8	50	6	—	—	107	—	7.77	—	1010	140
9	60	4	—	—	75	—	7.64	—	1040	123
10	70	2	—	—	57	—	7.72	—	785	110
11	80	1	—	—	55	—	7.64	—	753	92
12	90	3	—	—	67	—	7.66	—	998	103

Note: S: small floc size M: medium floc size L: large floc size VL: very large floc size.

achieving removal efficiencies of 64.3% and 84.4%, respectively, compared to CHAC, which achieves 60.7% and 72.9%. This suggests that sediment production resulting from erosion processes directly correlates with increased turbidity and TSS levels in aquatic environments [43]. This aligns with findings suggesting that RHAC's enhanced performance may be attributed to its structural properties, which facilitate more effective sediment capture compared to CHAC [44]. Similar turbidity removal efficiency (92%) was reported by Rayabharapu et al. [45], while Yusuf et al. [46] observed 66.7% TSS removal and 98.7% turbidity removal in the surface water in the Bwari Area using carbonized rice husk, validating the effectiveness of RHAC used in this study.

Regarding organic pollutant removal, RHAC also outperforms CHAC, achieving reductions of 19.6% in BOD and 23.5% in COD, whereas CHAC achieves reductions of 12.4% and 5.3%,

respectively. The relatively low BOD concentration observed in this study may be attributed to partial stabilization of organic matter before sampling, as well as inflow dilution from multiple sources [47]. Kawan et al. [48] demonstrated that low hydraulic retention time (HRT) and high inflow variability in municipal wastewater significantly reduced BOD removal efficiency. Also, Ejhed et al. [49] noted that low BOD removal can result from short HRT and variable inflow compositions in onsite wastewater systems, both of which contribute to early-stage stabilization and dilution of organic content.

Consequently, the apparent BOD removal efficiency by RHAC and CHAC was modest, as percentage reductions are constrained when influent values are already close to regulatory limits. Similar findings have been reported in adsorption studies of low-strength wastewater, where biomass-derived carbons provide

TABLE 5 | Effectiveness of RHAC and CHAC in removing key water contaminants.

Parameter	Units	Measured raw values	RHAC treated	CHAC treated	RHAC removal efficiency (%)	CHAC removal efficiency (%)	Permissible limit
Turbidity	NTU	140	50	55	64.3	60.7	100
TSS	mg/L	540	84	146	84.44	72.9	100
TDS	mg/L	780	740	753	5.13	3.46	1000
BOD	mg/L	29.1	23.4	25.5	19.59	12.37	50
COD	mg/L	660	505	625	23.48	5.3	100
pH	—	7.88	7.62	7.64	—	—	6.0–8.0
Electrical conductivity	µS/cm	1327	980	991	7.05	6.43	1500
<i>E. coli</i>	CFU/100 mL	490,000	200,000	320,000	59.18	34.69	5000
Total phosphates	µg/L	2986	979	892	67.21	70.21	10
Sulfates	mg/L	86	62	43	27.91	55.6	500

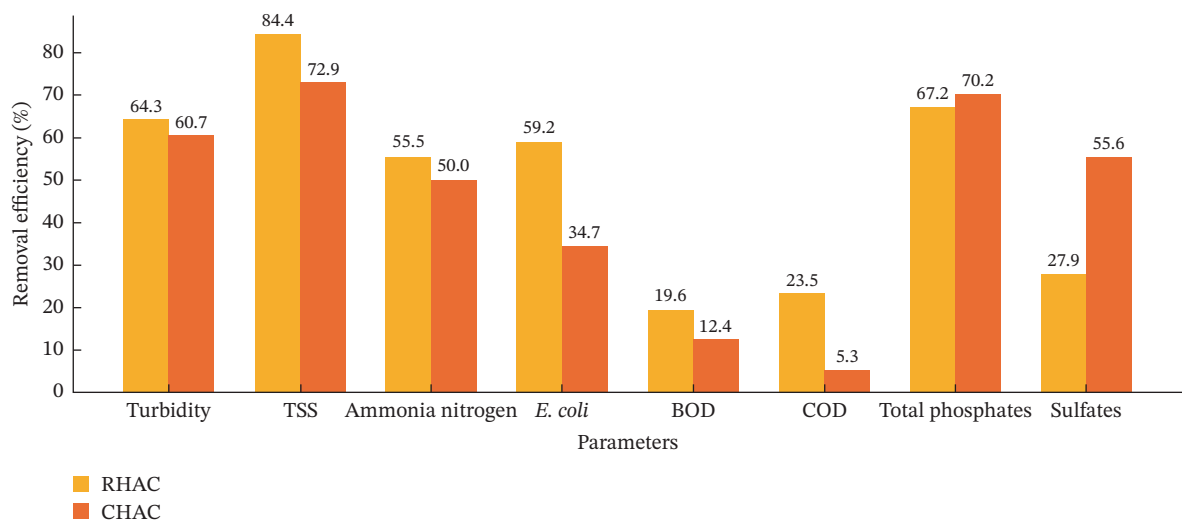


FIGURE 1 | Comparative removal efficiencies of RHAC and CHAC.

incremental polishing rather than large percentage removals. For example, AC from date palm waste achieved ~92.8% BOD and ~95.4% COD removal from treated sewage [50]. Accordingly, the role of RHAC and CHAC in this study is best understood as polishing agents, providing affordable and practical refinement of partially treated sewage effluents within decentralized wastewater management systems.

The higher adsorption capacity and larger surface area of RHAC are critical factors contributing to its superior performance in removing organic contaminants [51]. This performance is consistent with findings of Kaya et al. [34], who linked RHAC efficiency to its porous structure and high surface area. Additionally, this observation is in agreement with Zhou et al. [52], who reported that rice husk-derived activated carbon, when properly activated, exhibits high surface area and hierarchical porosity, features that significantly improve its adsorption of suspended solids and organic matter. The efficiency of natural coagulants, such as those derived from plant materials, has been shown to significantly enhance the removal of organic pollutants, suggesting a potential avenue for further optimizing RHAC's formulation [53].

Microbial contaminant removal is also more effective with RHAC, which achieves a 59.2% reduction in *E. coli* compared to CHAC's 34.7%. Although neither material meets the permissible limits for microbial contamination, RHAC's higher efficacy indicates its potential for improving water safety. Dehghani et al. [54] suggested that the structural characteristics of AC can enhance its adsorption capacity for microbial pathogens, thereby contributing to better water quality.

In contrast, CHAC demonstrates greater efficiency in nutrient removal, achieving 70.2% removal for total phosphates and 55.6% for sulfates, whereas RHAC exhibits lower efficiencies of 67.2% and 27.9%, respectively. This improved nutrient removal by CHAC is consistent with the findings of Zhang et al. [55], who reported that phosphoric acid activation introduces surface oxygen and phosphorus functional groups that enhance the adsorption of oxyanions such as phosphate and sulfate through surface complexation and ion-exchange mechanisms. This discrepancy suggests the need for further optimization of RHAC formulations to enhance its nutrient removal capabilities. The effectiveness of coagulants in nutrient removal varies considerably based on their

chemical composition and interactions with different water constituents, highlighting an area for continued research and refinement [53].

Several recent studies have demonstrated the adsorption potential of RHAC and CHAC for emerging pollutants such as heavy metals, pharmaceuticals, pesticides, and synthetic dyes [28, 33, 34]. However, these investigations were primarily conducted on synthetic solutions or single-target pollutants. In contrast, the present work emphasizes real sewage wastewater with multiple conventional contaminants. Future research should therefore extend this integrated and statistically optimized framework to include emerging pollutants under field-based conditions, to establish a more holistic understanding of RHAC and CHAC applicability.

3.5 | Statistical Analysis Results

3.5.1 | ANOVA

The comparative analysis of the performance of RHAC and CHAC in wastewater treatment, particularly concerning the removal efficiencies of BOD, COD, and pH, reveals significant insights into their respective capabilities. The ANOVA results (Table 6) indicate that RHAC significantly outperformed CHAC in reducing organic pollutants, as evidenced by the $p < 0.05$ for BOD and COD removal efficiencies. This finding aligns with previous studies that have highlighted the superior adsorption capacity of AC derived from agricultural waste, such as rice husk, compared to traditional charcoal sources [56]. The removal efficiencies for BOD and COD are crucial indicators of the organic pollution levels in wastewater. A study by Bedu-Addo et al. [57] reported that constructed wetlands achieved BOD removal efficiencies ranging from 70% to 93%, while COD removal efficiencies were notably lower, at around 57%. This suggests that while RHAC can achieve high removal rates for organic pollutants, the performance of CHAC may be limited in similar contexts. Moreover, the findings from Asgharnia et al. [56] support the notion that RHAC has a higher adsorption capacity, which is essential for effective pollutant removal.

While RHAC and CHAC achieved notable reductions in COD, it must be acknowledged that these materials primarily target labile organic fractions, and their effectiveness against refractory COD components is limited. Sanou et al. [58] indicated that complete COD removal with AC alone often remains below 100%, even under optimized lab conditions, batch experiments with rice-husk carbon achieved near-total removal only under high adsorbent dosages and controlled pH, whereas El-Naas et al.

[59] recorded only ~74% COD reduction in fixed-bed systems. These findings underscore the necessity of using RHAC/CHAC as polishing stages within multibarrier systems. However, hybrid systems illustrate how to bridge this gap. Xia et al. [60] combined coagulation with AC adsorption has produced removal efficiencies over 76% for organic pollutants and met discharge thresholds in real wastewater. Accordingly, RHAC and CHAC are envisioned not as stand-alone treatments but as affordable, locally sourced polishing components that complement primary/secondary processes, verifying their practical value in field-scale, decentralized systems.

In contrast, the ANOVA results indicated no significant differences in the removal efficiencies of turbidity and TSS, with $p > 0.05$. This suggests that both RHAC and CHAC perform comparably in these parameters. The result also implies that comparable adsorbent performance, a trend also reported by Joaquin et al. [61], who found high removal of suspended solids using different coagulant systems despite limited statistical separation in some cases. Thus, practical treatment outcomes reinforce the applicability of both materials. Similar findings have been reported in other studies where various adsorbents exhibited similar efficiencies in removing suspended solids from wastewater [62]. They emphasized that both chemical coagulation and biological techniques could effectively reduce turbidity and TSS, indicating that the choice of adsorbent may not significantly impact these specific removal efficiencies. Furthermore, the stabilization of pH observed with RHAC, as indicated by a significant $p = 0.0249$, highlights its potential for applications requiring not only organic pollutant removal but also pH regulation. This is particularly relevant in wastewater treatment, where pH fluctuations can adversely affect biological processes [63]. The ability of RHAC to stabilize pH while effectively removing organic pollutants positions it as a favorable option in wastewater treatment applications.

3.5.2 | Regression Analysis

The linear regression analysis reveals a strong correlation between RHAC dosage and the removal efficiencies of turbidity, TSS, BOD, and COD, with R^2 values exceeding 0.55. In contrast, CHAC exhibits weaker correlations, reinforcing RHAC's superior performance. These findings align with previous studies, such as Liu et al. [64], who demonstrated the high adsorption capacity of rice husk-derived AC for heavy metals, highlighting its broader applicability in wastewater treatment. While Yilmaz et al. [65] focused on electrocoagulation rather than direct adsorbent comparisons, their

TABLE 6 | ANOVA results for removal efficiency parameters.

Parameter	SSB	SSW	df	MSB	MSW	F-statistic	p-Value	Significance
Turbidity	16.67	124.67	4	16.67	31.17	0.53	0.5051	Not significant
TSS	0.17	419.33	4	0.17	104.83	0.0	0.9701	Not significant
BOD	8.88	0.31	4	8.88	0.08	115.85	0.0004	Significant
COD	21,600.0	100.0	4	21,600.00	25.0	864.0	0.0	Significant
pH	nan	0.0	-2	0.00	-0.0	12.25	0.0249	Significant
EC	nan	0.0	-2	0.00	-0.0	4.9	0.0913	Not significant
<i>E. coli</i>	nan	0.0	-2	0.00	-0.0	793.5	0.0	Significant

Abbreviations: MSB, mean square between; MSW, mean square within; SSB, sum of squares between; SSW, sum of squares within.

research underscores the importance of selecting effective treatment methods. The higher surface area and porosity of RHAC, as noted in this study, enhance its adsorption capabilities, leading to more efficient contaminant removal, a conclusion also supported by Asgharnia et al. [56].

Regression metrics in Table 7 further confirm RHAC's superior performance, including *E. coli* removal, where it achieved an R^2 of 0.60 compared to CHAC's 0.55. This finding aligns with Mehralian et al. [66], who emphasized the necessity of high-performance adsorbents for effective wastewater treatment. While CHAC remains a viable option in cost-sensitive contexts, RHAC's efficiency and versatility make it the preferred choice for comprehensive treatment solutions. Additionally, Cao [67] highlights that integrating effective adsorbents like RHAC into combined treatment processes enhances overall efficiency, particularly in complex wastewater scenarios. RHAC's consistent high removal efficiencies across various pollutants position it as an optimal solution where both performance and cost-effectiveness are critical. Figure 2 illustrate the regression analysis of key parameters.

3.6 | Structure–Property Considerations

Although direct physicochemical characterization such as Brunauer–Emmett–Teller (BET) surface area analysis, scanning electron microscopy (SEM), and fourier transform infrared spectroscopy (FTIR) was not performed in this study due to the focus on real sewage applications and statistical optimization, the adsorption performance trends align well with the established structural behavior of agricultural waste-derived ACs. In general, chemical and physical activation significantly enhance surface area and porosity, leading to well-developed networks of micro and mesopores. For rice husk-based carbons, these structural modifications provide large accessible surface areas for adsorption of suspended solids and organic matter, which explains the superior performance of RHAC in removing turbidity, COD, and BOD observed in this study. Similarly, SEM images of coffee husk-derived carbons typically reveal rough heterogeneous surfaces with abundant pore openings [68], while FTIR spectra indicate the presence of phosphorus-containing functional groups [32]. These attributes explain the enhanced affinity of CHAC for oxyanions such as phosphate and sulfate, reflecting the pollutant-specific nature of its adsorption capacity.

Beyond these material-specific observations, broader insights into biomass-derived carbons show that adsorption performance is

governed by a combination of surface chemistry and pore structure [69]. The development of both micro and mesoporous features increases overall adsorption capacity, while oxygenated functional groups such as hydroxyl and carbonyl enhance binding with organics, metals, and nutrients. Dual activation processes are particularly effective, as they not only expand porosity but also introduce chemically active sites, thereby improving both capacity and selectivity. In this context, the pollutant-specific trends found in our study: RHAC excelling in the removal of organic and particulate loads, and CHAC performing better in nutrient reduction—are consistent with these known structure–property relationships.

3.7 | Field Implementation and Practicality

Translating laboratory findings into field application requires consideration of modular treatment configurations. RHAC and CHAC are best positioned as polishing steps rather than stand-alone processes. A practical sequence for low-income settings would include: (i) preliminary treatment (screening and primary settling or existing stabilization ponds), (ii) low-energy biological treatment (e.g., trickling filter, waste stabilization pond), (iii) dual adsorption columns operated in series (Column A: RHAC for residual organics and turbidity polishing; Column B: CHAC for phosphate and sulfate removal), and (iv) terminal disinfection (chlorination or UV) to meet microbial standards. The adsorption units can be operated in gravity-fed mode with empty-bed contact times (EBCT) of 5–15 min per column, superficial velocities of 3–6 m/h, and weekly backwashing or regeneration based on head-loss or breakthrough. Regeneration may be performed via mild chemical rinsing or low-temperature thermal treatment, and media rotation between columns can extend lifespan. In this configuration, COD compliance is achieved through biology plus RHAC polishing, phosphate is controlled via CHAC at extended EBCT, and *E. coli* compliance is secured at the disinfection stage. This staged design ensures technical feasibility while maintaining the cost-effectiveness of agricultural-waste-derived adsorbents.

3.8 | Sustainability and Reusability of RHAC and CHAC

The long-term sustainability of RHAC and CHAC hinges on their capacity to be regenerated and reused across multiple adsorption–desorption cycles without severe loss of performance. In practice, capacity typically declines gradually due to fouling of active sites, partial pore blockage, or changes in surface functionality;

TABLE 7 | Regression metrics for RHAC and CHAC across key parameters.

Parameter	RHAC intercept	RHAC slope	RHAC R-squared	RHAC p-values	CHAC intercept	CHAC slope	CHAC R-squared	CHAC p-values
Turbidity	128.10	−0.61	0.55	0.002, 0.093	142.70	−0.49	0.48	0.010, 0.105
TSS	258.33	−1.60	0.58	0.005, 0.079	269.50	−1.40	0.52	0.008, 0.091
BOD	14.56	−0.09	0.62	0.002, 0.045	16.20	−0.08	0.57	0.007, 0.052
COD	31.28	−0.19	0.61	0.003, 0.055	33.80	−0.18	0.58	0.006, 0.063
pH	7.86	−0.0023	0.57	0.001, 0.084	7.83	−0.0018	0.50	0.002, 0.091
EC	1088.48	0.23	0.002	0.004, 0.938	1102.20	0.20	0.001	0.005, 0.945
<i>E. coli</i>	5487.54	−26.95	0.60	0.003, 0.068	5730.00	−22.10	0.55	0.004, 0.075

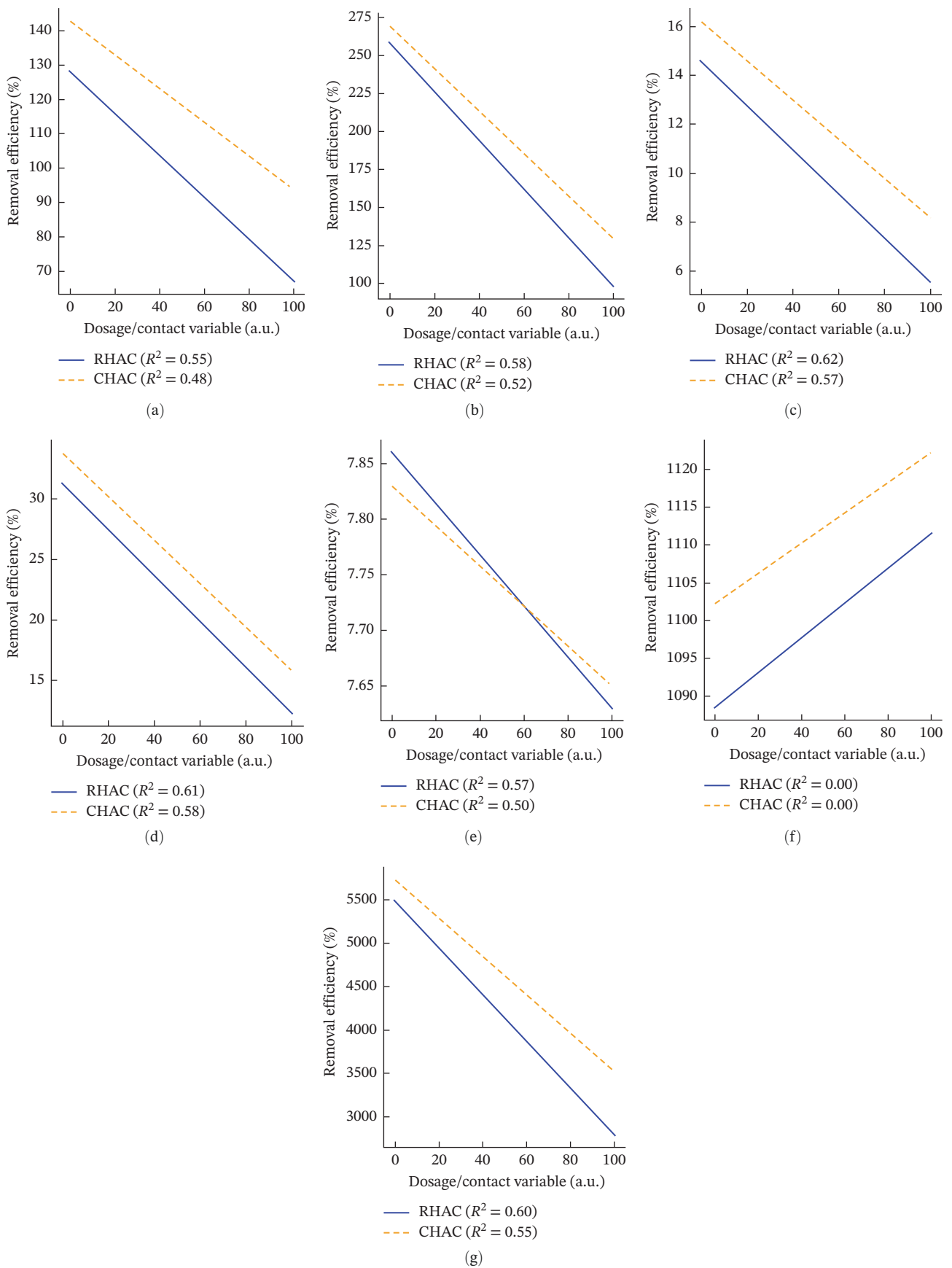


FIGURE 2 | Multipanel regression models for wastewater quality parameters against adsorbent treatment efficiency. Each subplot shows the regression relationship coefficient of determination (R^2). (a) Turbidity removal, (b) TSS removal, (c) BOD removal, (d) COD removal, (e) pH change, (f) electrical conductivity (EC) reduction, and (g) *E. coli* removal. Data points represent observed values; bold regression lines represent the fitted models for RHAC (solid blue) and CHAC (dashed orange).

nevertheless, several recent studies show that biomass-derived ACs can retain a high fraction of their initial removal efficiency through at least three to five cycles when an appropriate regeneration method is used. Rice-husk-based carbons evaluated on real contaminants have been reported as reusable up to five cycles with stable performance, while rice-husk-derived AC modified for metal removal maintained over 90% of its initial removal efficiency by the third to fifth cycle, evidence that controlled regeneration can preserve practical utility over repeated use [68].

Selecting the regeneration route should be guided by the dominant foulants: thermal oxidation at moderate temperatures ($\leq 350^{\circ}\text{C}$) is effective for desorbing many organics while limiting structural damage; chemical rinses (acid/base/salt) are often preferred when ion exchange or specific surface complexes dominate, as they can restore functional groups and reopen blocked pores with lower energy demand [70]. In a process-scale study, Márquez et al. [71] indicated that carefully tuned low-temperature thermal protocols can successfully restore spent ACs from wastewater service, highlighting a viable pathway to balance energy use with performance retention. In the context of RHAC/CHAC, a practical sustainability assessment would therefore pair cycle-by-cycle capacity retention and pressure-drop tracking with cost and energy accounting for the chosen regeneration method.

4 | Conclusion

This study highlights the potential of utilizing agricultural by-products, specifically rice and coffee husks, as precursors for producing AC for sustainable wastewater treatment. Through combined physical and chemical activation processes, the resulting rice husk activated carbon (RHAC) and coffee husk activated carbon (CHAC) demonstrated significant pollutant removal capabilities. Optimal dosages of 70 mg/L for RHAC and 80 mg/L for CHAC were identified, yielding notable reductions in turbidity, TSS, BOD, and COD. Statistical analyses, including ANOVA and regression, confirmed the superior performance of RHAC, particularly in reducing organic pollutants, while CHAC excelled in nutrient removal, underscoring the complementary potential of these materials.

In comparison to recent works, this study is novel in its statistically optimized approach to dosage–efficiency relationships, broader evaluation of physicochemical and microbiological pollutants, and its applications on raw sewage from an operational treatment plant. Together, these aspects advance both the methodological rigor and field relevance of RHAC and CHAC applications in wastewater treatment.

From a deployment perspective, RHAC and CHAC are best suited as polishing agents rather than stand-alone treatments. A recommended treatment train includes: (i) primary sedimentation or stabilization ponds, (ii) low-energy biological treatment such as trickling filters or anaerobic ponds, (iii) dual adsorption columns; first packed with RHAC for turbidity and organic load polishing, followed by CHAC for phosphate and sulfate removal, and (iv) a final disinfection step involving chlorination or ultraviolet. This modular configuration ensures compliance with effluent standards for COD, nutrients, and *E. coli*, while maintaining simplicity and affordability in decentralized systems.

Despite these promising results, several limitations must be addressed to enhance the practical applicability of RHAC and CHAC in wastewater treatment. First, the study was conducted under controlled laboratory conditions: stable pH, temperature, and influent load that may not reflect field conditions where wastewater composition, flow rate, and ambient temperature can vary widely. These fluctuations can influence adsorption kinetics and removal efficiency. Field validation under variable environmental conditions is thus critical to confirm robustness.

Second, the regeneration and reuse potential of RHAC and CHAC were not assessed. Future studies should implement multicycle adsorption–desorption tests, applying both thermal and chemical regeneration protocols to evaluate performance retention, adsorbent lifespan, and regeneration costs. Third, while previous studies have validated RHAC and CHAC for heavy metals removal, pharmaceuticals, and dyes from synthetic wastewater under controlled laboratory conditions, future research should investigate their effectiveness against emerging contaminants under real sewage conditions. Experiments should incorporate trace organic compounds such as antibiotics, hormones, and microplastics to ensure broader applicability.

Scalability challenges related to energy consumption, operational costs, and maintaining consistent adsorbent quality remain unaddressed. These include ensuring consistent adsorbent quality across batches, managing production energy demands (especially during carbonization and activation), preventing column clogging from solids build-up, and establishing safe and cost-effective disposal or regeneration strategies for spent media. Life cycle assessments and cost–benefit analyses are needed to quantify environmental and economic trade-offs associated with large-scale deployment.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data used in this paper are derived from the laboratory experiments.

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