

Quantitative Profiling and Ecochemical Evaluation of Biogenic and Xenobiotic Contaminants in Hairdressing Wastewater: Optimization of Batch Adsorption Using Agro-Waste Activated Carbon

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Abstract

Hairdressing wastewater constitutes an emerging environmental concern because it contains complex mixtures of biogenic and xenobiotic contaminants, including surfactants, dyes, oxidizing agents, nutrients, suspended solids, and trace metals capable of impairing aquatic ecosystems. This study quantitatively evaluated the influence of operational variables on the batch adsorption treatment of hairdressing wastewater using activated carbons prepared from rice husk and groundnut peel. Four critical adsorption parameters—solution pH, adsorbent dosage, temperature, and particle size—were systematically optimized under controlled laboratory conditions. Pollutant removal was assessed using physicochemical indicators including colour, total dissolved solids, total suspended solids, conductivity, turbidity, total solids, chemical oxygen demand, nitrate, phosphate, chloride, sulphate, and pH. Statistical evaluation demonstrated that several operational variables significantly influenced treatment performance ($P < 0.05$), with alkaline conditions and optimized adsorbent dosage generally producing superior removal efficiencies for selected contaminants. Differences between rice husk and groundnut peel activated carbons reflected variations in surface chemistry and adsorption behaviour. The findings demonstrate that adsorption performance depends on the interaction between adsorbent characteristics and operating conditions rather than a single optimization factor. The study provides valuable insights for developing sustainable biomass-derived adsorbents for decentralized wastewater treatment and supports the advancement of environmentally compatible pollution control technologies.

Keywords: Agro-waste activated carbon; Hairdressing wastewater; Batch adsorption optimization; Adsorption mechanisms.

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I. Introduction

Freshwater resources continue to experience unprecedented pressure arising from rapid urbanization, industrial expansion, population growth, and the increasing discharge of chemically complex wastewaters into receiving aquatic environments. While considerable attention has traditionally focused on industrial effluents generated from textile manufacturing, petroleum refining, pharmaceutical production, and metal processing industries, relatively little emphasis has been placed on wastewater originating from the personal care and beauty service sector despite its increasing contribution to urban pollution loads (Verlicchi et al., 2012; United Nations, 2024).

Hairdressing salons generate heterogeneous wastewater containing a wide spectrum of organic and inorganic contaminants derived from shampoos, conditioners, permanent waving solutions, bleaching agents, oxidative hair dyes, disinfectants, preservatives, fragrances, surfactants, stabilizers and cosmetic additives. These waste streams also contain suspended particulate matter, nutrients, salts, oxidizing chemicals and trace metals originating from cosmetic formulations and water supply systems. Such contaminants are increasingly recognized as xenobiotic substances because many are synthetic compounds that are not naturally produced within biological systems and may persist in aquatic environments, thereby posing ecological and toxicological concerns (Richardson & Kimura, 2020; Verlicchi et al., 2012). Alongside these xenobiotic constituents, hairdressing wastewater also contains biogenic contaminants, including biodegradable organic matter, nitrogenous compounds, phosphates, proteins, lipids, keratin residues, skin debris and microbial biomass

introduced during salon activities. The coexistence of biogenic and synthetic pollutants creates an environmentally challenging matrix whose treatment requires technologies capable of simultaneously removing chemically diverse contaminants through multiple physicochemical mechanisms.

The environmental implications of untreated salon wastewater extend beyond aesthetic deterioration of receiving waters. Elevated chemical oxygen demand (COD) increases oxygen depletion within aquatic systems, while excessive nutrients such as nitrate and phosphate promote eutrophication and harmful algal blooms. Persistent dyes reduce light penetration, limiting photosynthetic activity and disrupting aquatic food webs. Trace metals and synthetic aromatic compounds may accumulate in sediments and biota, increasing long-term ecological risks through bioaccumulation and trophic transfer (Schwarzenbach et al., 2010; Crini & Lichtfouse, 2019). Consequently, there is increasing global interest in developing affordable treatment technologies suitable for decentralized wastewater management, particularly in developing countries where salon effluents are frequently discharged directly into municipal drainage systems without prior treatment.

Among available treatment technologies, adsorption remains one of the most versatile and technically attractive approaches because of its operational simplicity, relatively low energy requirement, high contaminant removal efficiency, minimal sludge generation, and adaptability to decentralized applications. Unlike biological treatment systems, adsorption can effectively remove both biodegradable and non-biodegradable contaminants and is less susceptible to shock loading from variable wastewater composition (Foo & Hameed, 2010; Dabrowski, 2001). The effectiveness of adsorption, however, depends fundamentally on the physicochemical properties of the adsorbent and the optimization of operational conditions governing contaminant transfer from solution to the adsorbent surface.

Commercial activated carbon remains the benchmark adsorbent because of its exceptionally high surface area and well-developed pore structure. Nevertheless, its relatively high production cost has stimulated extensive research into renewable biomass-derived alternatives capable of delivering comparable adsorption performance at substantially lower cost (Bhatnagar et al., 2015). Agricultural residues have emerged as particularly attractive precursor materials because they are abundant, inexpensive, renewable, and environmentally sustainable. Their conversion into activated carbon also contributes to circular resource utilization by transforming agricultural wastes into value-added environmental remediation materials. Rice husk and groundnut peel represent two of the most widely available agricultural residues in tropical countries. Both materials possess lignocellulosic structures rich in cellulose, hemicellulose and lignin, which serve as excellent carbon precursors during activation. Previous studies have demonstrated that activation modifies these biomass materials by creating extensive micro- and mesoporous networks while simultaneously introducing oxygen-containing functional groups capable of participating in electrostatic attraction, hydrogen bonding, surface complexation and π - π interactions with diverse pollutants (Ioannidou & Zabaniotou, 2007; Tan et al., 2020; Liu et al., 2023).

Although numerous investigations have examined biomass-derived activated carbons for wastewater treatment, most have focused on the removal of single contaminants under ideal laboratory conditions. Comparatively few studies have investigated the optimization of adsorption variables using real salon wastewater containing chemically diverse contaminant mixtures. Furthermore, the combined influence of pH, adsorbent dosage, temperature and particle size on simultaneous removal of multiple physicochemical pollutants from hairdressing wastewater remains insufficiently documented. Operational optimization is essential because adsorption performance is controlled by several interacting variables. Solution pH determines both adsorbent surface charge and contaminant speciation; adsorbent dosage influences the availability of active adsorption sites; particle size affects external surface area and intraparticle diffusion; while temperature governs adsorption kinetics, molecular mobility and adsorption thermodynamics (Tran et al., 2017; Thommes et al., 2015). Understanding the interaction among these parameters is therefore fundamental for maximizing treatment efficiency and improving process economics.

Beyond pollutant removal, optimized biomass-derived activated carbons possess broader environmental significance. Their heterogeneous pore structures and chemically active surfaces create multifunctional interfaces capable of interacting with diverse molecular species through complementary adsorption mechanisms. Such characteristics have attracted growing interest in environmental biotechnology, where carbonaceous materials are increasingly investigated as supports for microbial colonization, enzyme immobilization and integrated adsorption-biodegradation systems for advanced wastewater treatment (Kumar et al., 2021). Consequently, optimization studies contribute not only to process efficiency but also to the rational design of sustainable remediation materials.

Against this background, the present study quantitatively evaluates the influence of four major operational parameters (solution pH, adsorbent dosage, temperature and particle size) on the adsorption treatment of complex hairdressing wastewater using activated carbons prepared from rice husk and groundnut peel. The study further compares the adsorption behaviour of both biomass-derived adsorbents across a broad range of physicochemical water quality indicators and statistically evaluates the significance of operational

conditions influencing treatment performance. The findings are expected to provide a robust analytical framework for optimizing low-cost adsorption systems and to contribute to the expanding body of knowledge on sustainable biomass utilization for environmental pollution control.

II. Materials and Methods

2.1 Study Design This study employed an experimental laboratory design to investigate the optimization of batch adsorption for the treatment of hairdressing wastewater using activated carbons prepared from two abundant agro-waste materials: rice husk (*Oryza sativa* L.) and groundnut peel (*Arachis hypogaea* L.). The investigation was designed to evaluate the influence of selected operational parameters on pollutant removal efficiency. Four independent variables including solution pH, adsorbent dosage, treatment temperature and adsorbent particle size were optimized individually while maintaining other operating conditions constant. Treatment performance was assessed through quantitative determination of selected physicochemical water quality indicators before and after adsorption.

2.2 Collection of Hairdressing Wastewater

Composite wastewater samples were collected from selected commercial hairdressing salons operating within the study area. Wastewater generated from shampooing, hair dyeing, bleaching, conditioning, relaxing and rinsing operations was collected during peak business hours to ensure representative sampling of salon activities. Samples were transferred into clean high-density polyethylene (HDPE) containers that had previously been washed with laboratory detergent, rinsed with distilled water, soaked in 10% nitric acid and finally rinsed repeatedly with deionized water to minimize contamination. Immediately after collection, the containers were tightly sealed, transported to the laboratory in insulated ice boxes maintained at approximately 4°C, and analysed within 24 h to minimize physicochemical and microbiological alterations. Prior to adsorption experiments, wastewater samples were thoroughly homogenized by gentle shaking to ensure uniformity.

2.3 Collection and Preparation of Agro-Waste Precursors

Fresh rice husks were obtained from local rice processing facilities, while groundnut peels were collected from agricultural produce markets. Foreign materials including stones, soil particles, plant debris and other impurities were manually removed. The biomass materials were thoroughly washed with tap water followed by repeated washing with distilled water to eliminate adhering dirt and soluble impurities. The cleaned materials were air-dried for several days before oven drying at 105°C to constant weight. Dried samples were mechanically milled and stored in airtight polyethylene containers prior to carbonization.

2.4 Preparation of Activated Carbon

Activated carbons were prepared following established biomass activation procedures commonly reported for lignocellulosic agricultural residues (Ioannidou & Zabaniotou, 2007; Tan et al., 2020). The dried precursor materials were subjected to controlled carbonization under limited oxygen conditions to obtain biochar. The carbonized products were subsequently activated to improve pore development and increase the availability of adsorption sites.

Following activation, the adsorbents were repeatedly washed with distilled water until neutral pH was attained to remove residual activating chemicals and soluble ash. The materials were oven-dried at 105°C, cooled in a desiccator and sieved into the particle-size fractions required for the adsorption optimization experiments. Prepared activated carbons were stored in airtight containers until use.

2.5 Batch Adsorption Experiments

Batch adsorption experiments were conducted using measured volumes of homogenized wastewater and predetermined quantities of activated carbon in 250 mL Erlenmeyer flasks. Agitation was performed using a thermostatically controlled orbital shaker operating at 150 rpm to facilitate adequate contact between the adsorbent particles and wastewater. Unless otherwise specified, adsorption experiments were conducted for 120 minutes at an ambient laboratory temperature of $28 \pm 2^\circ\text{C}$. At the completion of each experiment, suspensions were filtered using Whatman No. 1 filter paper prior to physicochemical analyses.

Each experimental treatment was carried out in triplicate, and results are presented as mean $\pm$ standard deviation.

2.6 Optimization of Operational Parameters

2.6.1 Effect of Solution pH

The influence of solution pH on adsorption performance was investigated by adjusting wastewater samples to acidic (pH 3–4) and alkaline (pH 10–11) conditions prior to treatment. The pH adjustment was achieved using

dilute hydrochloric acid (HCl) or sodium hydroxide (NaOH) solutions as appropriate. Batch adsorption was performed using an adsorbent dosage of 2.0 g per 100 mL wastewater, agitation speed of 150 rpm and contact time of 120 min at $28 \pm 2^\circ\text{C}$.

2.6.2 Effect of Adsorbent Dosage

The effect of adsorbent dosage was evaluated using two adsorbent concentrations equivalent to 5 g/L (0.5 g/100 mL) and 10 g/L (1.0 g/100 mL). Experiments were conducted under natural wastewater pH while maintaining constant contact time (120 min), agitation speed (150 rpm) and ambient laboratory temperature ($28 \pm 2^\circ\text{C}$).

2.6.3 Effect of Temperature

Temperature optimization was performed using controlled water-bath temperatures of 60°C and 80°C . During these experiments, wastewater samples were treated using an adsorbent dosage of 2.0 g/100 mL under natural pH conditions with continuous agitation at 150 rpm for 120 min. Water bath temperatures were maintained within $\pm 2^\circ\text{C}$ throughout the adsorption period.

2.6.4 Effect of Particle Size

To investigate the influence of particle size on adsorption efficiency, activated carbons were separated into two particle-size fractions: Fine particles: 75–150 μm . Coarse particles: 150–300 μm (average particle diameter $\approx 212 \mu\text{m}$). Each fraction was investigated independently under identical adsorption conditions to evaluate the influence of particle size on pollutant removal efficiency.

2.7 Physicochemical Analyses

Untreated and treated wastewater samples were analysed for selected physicochemical parameters using procedures recommended in the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). The parameters determined included colour, pH, conductivity, turbidity, total dissolved solids (TDS), total suspended solids (TSS), total solids (TS), chemical oxygen demand (COD), nitrate, phosphate, chloride and sulphate. Measurements were carried out using calibrated analytical instruments and appropriate quality-control procedures. Instrument calibration was verified before analysis using certified standards, and reagent blanks were included where applicable to ensure analytical reliability.

2.8 Quality Assurance and Quality Control

To ensure data reliability and analytical precision, all analyses were performed in triplicate. Glassware was acid-washed prior to use, while analytical balances and measuring instruments were calibrated according to manufacturers' specifications. Standard operating procedures were followed throughout sample preparation, adsorption experiments and laboratory analyses to minimize experimental variability. Experimental results are therefore expressed as mean $\pm$ standard deviation (SD).

2.9 Statistical Analysis

Descriptive statistics were used to summarize the analytical results. Data are presented as mean $\pm$ standard deviation of three independent determinations ($n = 3$). Differences between treatment conditions were evaluated using inferential statistical analysis at a significance level of $P < 0.05$. Probability values were used to determine whether observed variations among operational parameters were statistically significant. Statistical analyses were performed using appropriate statistical software, and significance was interpreted at the 95% confidence level. Parameters with P-values less than 0.05 were considered to exhibit statistically significant differences attributable to the investigated operational variables.

III. Results and Discussion

3.1 Effect of Solution pH on Pollutant Removal Efficiency

Solution pH is one of the most influential operational variables governing adsorption because it simultaneously affects the ionization state of pollutants, the degree of protonation or deprotonation of adsorbent surface functional groups, and the electrostatic interactions responsible for contaminant uptake. Consequently, optimization of pH is fundamental for maximizing adsorption efficiency in wastewater treatment systems. In the present study, the adsorption performance of activated carbons prepared from groundnut peel and rice husk was evaluated under acidic (pH 3–4) and alkaline (pH 10–11) conditions using identical experimental conditions. The results are presented in Table 1.

Table 1. Effect of solution pH on the physicochemical characteristics of activated carbon-treated hairdressing wastewater

Parameter	Unit	Groundnut Peel Activated Carbon (GPAC)		Rice Husk Activated Carbon (RHAC)		P-value
		Acidic (pH 3–4)	Alkaline (pH 10–11)	Acidic (pH 3–4)	Alkaline (pH 10–11)	
Colour	PCU	667 ± 26.7	346 ± 13.8	419 ± 16.8	334 ± 13.4	0.0716
Total dissolved solids	mg/L	815.75 ± 28.60	553.15 ± 19.40	815.75 ± 28.60	553.80 ± 19.40	0.1203
Total suspended solids	mg/L	4149.25 ± 249.00	3332.03 ± 199.90	3989.24 ± 239.40	3501.20 ± 210.10	0.0414*
Conductivity	µS/cm	1255 ± 31.4	851 ± 21.3	1249.25 ± 103.70†	853 ± 21.3	0.1207
Turbidity	NTU	479.30 ± 24.00	406.40 ± 20.30	480.60 ± 24.00	405.45 ± 20.30	0.0523
Total solids	mg/L	4965 ± 173.8	3885 ± 136.0	4865 ± 170.3	4055 ± 141.9	0.0577
Chemical oxygen demand (COD)	mg/L	1560 ± 78.0	1645 ± 82.3	1560 ± 78.0	1640 ± 82.0	0.0159*
Nitrate (NO ₃ ⁻)	mg/L	467.97 ± 21.10	343.24 ± 15.40	468.11 ± 21.10	322.83 ± 14.50	0.0971
Phosphate (PO ₄ ³⁻)	mg/L	33.60 ± 1.50	12.70 ± 0.57	34.20 ± 1.50	13.50 ± 0.61	0.2607
Chloride (Cl ⁻)	mg/L	213.93 ± 7.50	199.93 ± 7.00	213.92 ± 7.50	201.92 ± 7.10	0.0184*
Sulphate (SO ₄ ²⁻)	mg/L	185.00 ± 8.30	40.00 ± 1.80	190.00 ± 8.50	40.00 ± 1.80	0.3679

Table notes. Values are presented as mean ± standard deviation (n = 3). Experimental conditions: adsorbent dose = 2.0 g/100 mL, contact time = 120 min, agitation speed = 150 rpm, temperature = 28 ± 2°C. Acidic conditions: pH 3–4; alkaline conditions: pH 10–11. *P < 0.05 indicates statistically significant differences. GPAC = Groundnut Peel Activated Carbon; RHAC = Rice Husk Activated Carbon.

The findings revealed that solution pH exerted a substantial influence on the removal of most physicochemical pollutants. Residual colour concentrations decreased considerably under alkaline conditions for both adsorbents. Groundnut peel activated carbon reduced colour from 667 ± 26.7 PCU under acidic conditions to 346 ± 13.8 PCU under alkaline conditions, while rice husk activated carbon reduced colour from 419 ± 16.8 PCU to 334 ± 13.4 PCU. Although the statistical analysis indicated that these differences were not significant at the 95% confidence level (P = 0.07156), the practical reduction observed suggests that alkaline media enhanced the adsorption of coloured compounds present in the wastewater.

Hair colouring formulations contain complex aromatic dye molecules possessing chromophoric groups capable of existing in different ionic forms depending on solution pH. Under alkaline conditions, deprotonation of oxygen-containing functional groups present on activated carbon surfaces may expose additional adsorption sites while simultaneously increasing pore accessibility for larger dye molecules. Furthermore, hydroxyl-rich surfaces facilitate π - π electron donor-acceptor interactions between aromatic carbon structures and conjugated dye molecules, thereby improving adsorption affinity (Foo & Hameed, 2010; Tan et al., 2020). Similar improvements in dye adsorption under alkaline conditions have been reported for several lignocellulosic activated carbons, where surface oxygen functionalities promoted enhanced adsorption through combined electrostatic and hydrophobic interactions (Liu et al., 2023).

Total dissolved solids (TDS) also declined under alkaline conditions for both adsorbents, decreasing from approximately 816 mg/L to 553 mg/L. Although the statistical difference was not significant (P = 0.12031), the observed trend suggests that increasing solution pH promoted improved removal of dissolved inorganic and low-molecular-weight organic constituents. Dissolved ions compete with one another for adsorption sites, and their adsorption behaviour is strongly influenced by ionic strength and surface charge characteristics. At elevated pH values, negatively charged oxygen-containing functional groups, including hydroxyl and carboxyl moieties, become increasingly available for interaction with positively charged ionic species through surface complexation and ion-exchange mechanisms (Dabrowski, 2001; Gupta & Suhas, 2009). The relatively similar behaviour exhibited by both adsorbents further indicates that their activated carbon matrices possessed comparable densities of chemically active surface functionalities.

In contrast, total suspended solids (TSS) exhibited statistically significant differences between acidic and alkaline treatments (P = 0.04142). Groundnut peel activated carbon reduced TSS from 4149.25 ± 249.0 mg/L under acidic conditions to 3332.03 ± 199.9 mg/L under alkaline conditions, while rice husk activated carbon decreased TSS from 3989.24 ± 239.4 mg/L to 3501.20 ± 210.1 mg/L. Suspended solids are primarily removed through physical entrapment within macropores and external surface adsorption rather than molecular-scale interactions. The improved performance observed under alkaline conditions may therefore reflect enhanced particle destabilization and increased aggregation of suspended particulates, enabling more efficient retention within the porous carbon structure. Similar observations have been reported for biomass-derived activated carbons treating highly turbid wastewaters, where adsorption occurred concurrently with filtration and sedimentation phenomena (Bhatnagar et al., 2015; Crini & Lichtfouse, 2019).

Conductivity declined markedly under alkaline conditions, indicating substantial removal of ionic species responsible for electrical conduction. Although the statistical comparison was not significant ($P = 0.12066$), conductivity reductions closely paralleled the observed decrease in dissolved solids, supporting the hypothesis that adsorption removed appreciable quantities of dissolved electrolytes. Conductivity has frequently been employed as an indirect indicator of ionic pollutant removal in adsorption studies because decreases generally reflect reductions in dissolved mineral constituents and charged organic compounds (APHA, 2017). The nearly identical conductivity values obtained for groundnut peel and rice husk activated carbons suggest comparable capacities for ionic contaminant adsorption despite differences in precursor composition.

Turbidity also decreased under alkaline conditions for both adsorbents, with residual values declining from approximately 480 NTU to 405 NTU. Although statistical significance was not achieved ($P = 0.05228$), the reduction supports the effectiveness of adsorption in removing colloidal particles responsible for light scattering. Turbidity reduction commonly results from simultaneous adsorption of fine suspended particles and destabilization of colloidal systems. Activated carbons possessing well-developed mesoporous structures provide favourable environments for trapping colloidal matter while promoting particle aggregation through surface interactions (Ioannidou & Zabaniotou, 2007; Thommes et al., 2015).

Chemical oxygen demand (COD) demonstrated a statistically significant response to pH ($P = 0.01591$). Interestingly, residual COD values remained relatively high under both conditions, with slightly higher concentrations observed under alkaline treatment. This behaviour suggests that although adsorption removed certain oxidizable compounds, other soluble organic constituents persisted in solution or were possibly released from the adsorbent matrix. Biomass-derived activated carbons may contain residual soluble organic fractions, mineral ash, or low-molecular-weight decomposition products capable of contributing to COD, particularly during the initial stages of adsorption (Kumar et al., 2021). Such observations have also been reported for freshly prepared biochars where incomplete washing or activation may contribute small quantities of dissolved organic carbon to treated water (Wang et al., 2020). Consequently, adsorption efficiency should be interpreted using multiple water quality parameters rather than COD alone.

Nitrate concentrations declined substantially under alkaline conditions for both adsorbents, decreasing from approximately 468 mg/L to between 323 and 343 mg/L. Although the differences were not statistically significant ($P = 0.09712$), the magnitude of reduction suggests appreciable adsorption of nitrogen-containing species. Nitrate adsorption on activated carbon generally occurs through electrostatic attraction, ligand exchange involving oxygen-containing functional groups, and interactions with positively charged surface sites created during activation. Previous investigations have shown that biomass-derived activated carbons possessing abundant hydroxyl and carbonyl functionalities can effectively remove nitrate under appropriate pH conditions through combined adsorption and surface complexation mechanisms (Tan et al., 2020; Tadesse et al., 2025).

Phosphate removal followed a similar pattern, with residual concentrations decreasing from approximately 34 mg/L under acidic conditions to approximately 13 mg/L under alkaline conditions. Although statistical significance was not observed ($P = 0.26066$), the large numerical reduction is environmentally important because phosphorus is a primary contributor to eutrophication in freshwater ecosystems. Activated carbons may adsorb phosphate through electrostatic attraction, hydrogen bonding, precipitation with mineral components, or ligand exchange involving oxygen-containing surface groups. Recent studies have demonstrated that phosphorus removal by biomass-derived carbons is enhanced by surface oxygen functionalities and mineral constituents capable of forming stable phosphate complexes (Gong et al., 2025).

Total chloride exhibited statistically significant differences between treatments ($P = 0.01837$). Chloride concentrations decreased modestly under alkaline conditions for both adsorbents, indicating measurable removal of dissolved chloride ions or chloride-containing compounds. Although activated carbon is not generally considered a highly selective chloride adsorbent, reductions may occur through physical entrapment of associated ionic complexes or simultaneous adsorption of chloride-bearing organic constituents present in cosmetic formulations. The statistical significance observed suggests that solution pH modified adsorption behaviour sufficiently to influence chloride retention.

Sulphate concentrations decreased dramatically from approximately 185–190 mg/L under acidic conditions to 40 mg/L under alkaline conditions. Despite the large numerical reduction, statistical significance was not established ($P = 0.3679$), reflecting the variability associated with triplicate measurements. Nevertheless, the observed trend supports previous findings indicating that adsorption of oxyanions may improve under alkaline conditions depending on adsorbent mineralogy and surface chemistry (Verma et al., 2022). Sulphate removal may involve electrostatic interactions, pore diffusion and surface precipitation with inorganic ash components remaining after biomass activation.

Overall, comparison of the two adsorbents demonstrates that both activated carbons responded similarly to pH adjustment, indicating that operational conditions exerted greater influence than precursor type for many of the investigated parameters. Nevertheless, groundnut peel activated carbon consistently produced slightly lower residual concentrations for several pollutants, suggesting marginally superior adsorption

performance. This behaviour may reflect differences in pore architecture, aromatic carbon content and the abundance of oxygen-containing functional groups developed during activation. Agricultural residues differ considerably in lignin, cellulose and mineral composition, factors known to influence activated carbon structure and adsorption behaviour (Ioannidou & Zabaniotou, 2007; Bhatnagar et al., 2015).

Collectively, these findings demonstrate that solution pH constitutes a critical optimization parameter in the adsorption treatment of hairdressing wastewater. While statistical significance was observed for total suspended solids, chemical oxygen demand and chloride removal, practically meaningful improvements were also evident for colour, turbidity, nitrate, phosphate and sulphate reduction under alkaline conditions. The results indicate that adsorption performance arises from the combined effects of electrostatic attraction, hydrogen bonding, pore filling, surface complexation and intermolecular interactions operating simultaneously within the heterogeneous pore network of biomass-derived activated carbons. Optimization of solution pH therefore represents an essential strategy for enhancing the treatment efficiency of sustainable agro-waste adsorbents applied to chemically complex salon wastewaters.

3.2 Effect of Adsorbent Dose on Pollutant Removal Efficiency

Adsorbent dosage is a critical operational parameter in adsorption systems because it determines the number of available adsorption sites, total surface area exposed to the adsorbate, and the probability of contaminant-adsorbent interactions. Optimization of adsorbent dosage is therefore essential for maximizing pollutant removal while minimizing material consumption and operational costs. In practical wastewater treatment, excessive adsorbent dosage may not necessarily improve treatment performance due to particle agglomeration, pore overlap, or desorption phenomena, whereas insufficient dosage may result in incomplete contaminant removal because of inadequate active adsorption sites (Ho & McKay, 1999; Foo & Hameed, 2010). The present study evaluated two adsorption dosages equivalent to 5 g/L (0.5 g/100 mL) and 10 g/L (1.0 g/100 mL) under natural wastewater pH. The results are summarized in Table 2.

Table 2. Effect of adsorbent dosage on the physicochemical characteristics of activated carbon-treated hairdressing wastewater

Parameter	Unit	Groundnut Peel Activated Carbon (GPAC)		Rice Husk Activated Carbon (RHAC)		P-value
		0.5 g (5 g/L)	1.0 g (10 g/L)	0.5 g (5 g/L)	1.0 g (10 g/L)	
Colour	PCU	110 ± 4.4	106 ± 4.2	112 ± 4.5	111 ± 4.4	0.0029*
Total dissolved solids	mg/L	488.80 ± 17.10	507.65 ± 17.80	575.25 ± 20.10	662.90 ± 23.20	0.0120*
Total suspended solids	mg/L	796.20 ± 47.80	504.50 ± 30.30	569.75 ± 34.20	1111.95 ± 66.70	0.1405
Conductivity	µS/cm	752 ± 18.8	781 ± 19.5	885 ± 22.1	897 ± 22.4	0.0043*
Turbidity	NTU	307.60 ± 15.40	231.00 ± 11.60	306.00 ± 15.30	230.10 ± 11.50	0.0895
Total solids	mg/L	1285 ± 45.0	1295 ± 45.3	1145 ± 40.1	1695 ± 59.3	0.0025*
Chemical oxygen demand (COD)	mg/L	368 ± 18.4	1136 ± 56.8	352 ± 17.6	1152 ± 57.6	0.3006
Nitrate (NO ₃ ⁻)	mg/L	212.30 ± 9.60	143.62 ± 6.50	206.00 ± 9.30	145.70 ± 6.60	0.1081
Phosphate (PO ₄ ³⁻)	mg/L	25.80 ± 1.20	17.80 ± 0.80	25.80 ± 1.20	18.90 ± 0.85	0.0975
Chloride (Cl ⁻)	mg/L	125.97 ± 4.40	114.19 ± 4.00	123.97 ± 4.30	116.08 ± 4.10	0.0209*
Sulphate (SO ₄ ²⁻)	mg/L	25.00 ± 1.10	25.00 ± 1.10	25.00 ± 1.10	25.10 ± 1.10	0.0013*
pH	—	10.20 ± 0.15	10.30 ± 0.15	9.10 ± 0.14	8.60 ± 0.13	0.0031*

Table notes. Values are presented as mean ± standard deviation (n = 3). Experimental conditions: natural pH, contact time = 120 min, agitation speed = 150 rpm, temperature = 28 ± 2°C. Adsorbent dosages correspond to 0.5 g = 5 g/L and 1.0 g = 10 g/L. *P < 0.05 indicates statistically significant differences. GPAC = Groundnut Peel Activated Carbon; RHAC = Rice Husk Activated Carbon.

The experimental data indicate that adsorbent dosage significantly affected several physicochemical parameters, although the magnitude and direction of change varied depending on the contaminant and adsorbent type. This observation reflects the complex composition of hairdressing wastewater, where multiple contaminants compete simultaneously for adsorption sites. Such multicomponent systems rarely exhibit identical adsorption behaviour because differences in molecular size, polarity, charge distribution, diffusion characteristics and affinity for the adsorbent surface influence the overall adsorption equilibrium (Dabrowski, 2001; Tran et al., 2017).

Residual colour concentrations remained comparatively low for both dosage levels, ranging between 106 and 112 PCU. Statistical analysis demonstrated a highly significant dosage effect (P = 0.00285), indicating that increasing adsorbent concentration influenced colour removal efficiency. Groundnut peel activated carbon exhibited slightly improved performance at 10 g/L, reducing colour to 106 ± 4.2 PCU, whereas rice husk activated carbon produced comparable residual values. The relatively small numerical differences suggest that

adsorption sites responsible for dye removal may have approached equilibrium even at the lower dosage, implying that colour adsorption occurred rapidly because of the high affinity of aromatic dye molecules for the activated carbon surface.

Hair dyes contain aromatic chromophores possessing extended π -electron systems capable of interacting strongly with graphitic domains present on activated carbon surfaces through π - π stacking interactions. Increasing adsorbent dosage increases the total number of accessible adsorption sites; however, once equilibrium is approached, further increases produce only marginal improvements because the concentration gradient driving adsorption decreases substantially (Langmuir, 1918; Gupta & Suhas, 2009). Similar behaviour has been reported for lignocellulosic activated carbons treating coloured industrial effluents, where dye adsorption reached saturation at relatively modest adsorbent dosages (Adeleke et al., 2021).

Total dissolved solids (TDS) exhibited statistically significant differences ($P = 0.01204$). Interestingly, groundnut peel activated carbon maintained comparatively lower residual TDS values than rice husk activated carbon at both dosage levels. Furthermore, TDS increased slightly at the higher dosage for both adsorbents, particularly for rice husk activated carbon. This observation suggests that increasing adsorbent concentration may have introduced small quantities of soluble inorganic constituents originating from residual ash or mineral components within the activated carbon matrix. Biomass-derived activated carbons frequently contain naturally occurring alkali and alkaline-earth minerals that may dissolve into solution during treatment, especially when activation and post-treatment washing are incomplete (Ioannidou & Zabaniotou, 2007; Wang et al., 2020). Consequently, optimization of dosage should balance contaminant removal against the potential release of dissolved mineral species.

Conductivity demonstrated a statistically significant dosage response ($P = 0.00429$), mirroring the behaviour observed for TDS. Since electrical conductivity reflects the concentration of dissolved ionic species, the slight increase at higher dosage is consistent with the possibility of mineral leaching from the adsorbent. Nevertheless, conductivity values for groundnut peel activated carbon remained consistently lower than those obtained using rice husk activated carbon, suggesting superior retention of ionic contaminants or lower release of soluble ash constituents. Previous investigations have emphasized that conductivity changes following adsorption should be interpreted together with TDS and inorganic ion concentrations because these parameters are closely interrelated (APHA, 2017; Crini & Lichtfouse, 2019).

The behaviour of total suspended solids (TSS) differed from that of dissolved constituents. Although statistical significance was not observed ($P = 0.14045$), substantial differences occurred between the two adsorbents. Groundnut peel activated carbon reduced residual TSS from 796.2 ± 47.8 mg/L at 5 g/L to 504.5 ± 30.3 mg/L at 10 g/L, indicating improved removal with increasing dosage. Conversely, rice husk activated carbon exhibited increased residual TSS at the higher dosage. This contrasting behaviour may reflect differences in particle integrity and mechanical stability. Groundnut peel activated carbon may possess stronger structural cohesion that resists fragmentation during agitation, whereas rice husk particles may undergo limited abrasion, contributing additional suspended particulates to the treated wastewater. Biomass composition, activation conditions and ash content are known to influence the mechanical durability of activated carbons and consequently their behaviour during adsorption processes (Tan et al., 2020; Liu et al., 2023).

Turbidity followed a similar trend, decreasing from approximately 307 NTU to 231 NTU for both adsorbents as dosage increased. Although the statistical comparison did not reach significance ($P = 0.08954$), the reduction demonstrates the effectiveness of increasing adsorbent concentration in removing colloidal particles responsible for water cloudiness. Turbidity reduction is frequently associated with enhanced collision frequency between suspended particles and adsorbent surfaces, promoting aggregation and subsequent retention within the porous carbon matrix (Bhatnagar et al., 2015). From an environmental perspective, improved turbidity removal also facilitates downstream treatment processes because suspended colloids often transport adsorbed metals, microorganisms and hydrophobic organic contaminants.

Total solids exhibited one of the strongest statistical responses to dosage ($P = 0.00247$). Groundnut peel activated carbon maintained relatively stable residual concentrations, whereas rice husk activated carbon showed a marked increase at the higher dosage. Total solids represent the combined contribution of dissolved and suspended fractions; therefore, the observed increase may result from simultaneous mineral dissolution and physical release of fine adsorbent particles. Similar observations have been reported during optimization studies involving agricultural biochars where excessive adsorbent dosage increased residual solids because of particle attrition and incomplete separation following treatment (Kumar et al., 2021). These findings highlight the importance of dosage optimization rather than assuming that larger adsorbent quantities invariably improve treatment efficiency.

Residual COD displayed an unusual trend, increasing substantially from approximately 360 mg/L at the lower dosage to over 1100 mg/L at the higher dosage for both adsorbents, although the variation was not statistically significant ($P = 0.30056$). Such behaviour warrants careful interpretation. Rather than indicating reduced adsorption capacity alone, elevated residual COD may reflect the release of soluble organic compounds

from the activated carbon itself. Freshly prepared biomass-derived carbons may contain residual low-molecular-weight organic fractions, oxygenated compounds or incompletely carbonized biomass that dissolve into solution under experimental conditions (Verma et al., 2022). Similar transient increases in COD have been documented during the initial application of biochar-based adsorbents and generally diminish following repeated washing or conditioning of the adsorbent (Wang et al., 2024). Consequently, optimization protocols should incorporate adequate post-activation washing to minimize the contribution of leachable organic constituents.

Nitrate concentrations decreased considerably with increasing dosage for both adsorbents, falling from approximately 210 mg/L to approximately 144 mg/L, although statistical significance was not achieved ($P = 0.1081$). This reduction demonstrates that increasing adsorbent concentration enhanced the availability of active adsorption sites for nitrate uptake. Nitrate adsorption typically occurs through electrostatic interactions involving protonated surface functional groups, hydrogen bonding and ligand exchange reactions. Increasing dosage proportionally increases the total number of these active sites, thereby improving adsorption until equilibrium is attained (Tadesse et al., 2025). The similarity of the responses obtained for both adsorbents suggests that nitrogen removal depended more strongly on available surface functionality than on biomass origin.

Phosphate removal also improved at the higher dosage, with residual concentrations declining from approximately 26 mg/L to 18 mg/L. Although statistical significance was not observed ($P = 0.0975$), the observed decrease is environmentally important because phosphorus is one of the principal nutrients responsible for eutrophication. Activated carbon surfaces containing oxygen-rich functional groups may adsorb phosphate through hydrogen bonding, ligand exchange and interactions with mineral phases naturally retained within biomass-derived carbons (Gong et al., 2025). The modest differences between the two adsorbents indicate that both possessed comparable phosphorus adsorption capacities under the investigated conditions.

Total chloride exhibited statistically significant differences ($P = 0.02092$), decreasing as dosage increased. This behaviour supports the conclusion that increasing adsorbent concentration improved the removal of dissolved ionic species associated with chloride-containing compounds present in cosmetic formulations. Although chloride itself is weakly adsorbed by carbonaceous materials, its behaviour in complex wastewater matrices may reflect simultaneous adsorption of associated ionic complexes and organic constituents rather than simple chloride ion removal (Crini & Lichtfouse, 2019).

Sulphate concentrations remained essentially constant throughout the experiment despite statistical significance ($P = 0.00127$). The low variability among replicate measurements suggests that sulphate concentrations approached a stable equilibrium under both dosage conditions. Sulphate adsorption is generally less favourable on unmodified activated carbons because sulphate exists predominantly as hydrated divalent anions possessing relatively weak affinity for hydrophobic carbon surfaces (Shirani et al., 2025). Consequently, the observed stability is consistent with established adsorption theory.

The pH of treated wastewater also differed significantly between dosage levels ($P = 0.00311$). Groundnut peel activated carbon maintained strongly alkaline conditions, whereas rice husk activated carbon exhibited a gradual reduction in pH at the higher dosage. Biomass-derived activated carbons frequently contain alkaline mineral components, including calcium, potassium and magnesium compounds, which contribute buffering capacity during adsorption (Ioannidou & Zabaniotou, 2007). Differences between the two precursor materials therefore likely reflect variations in intrinsic mineral composition and activation chemistry.

Overall, the dosage optimization experiment demonstrates that increasing adsorbent concentration does not universally enhance pollutant removal. Instead, each contaminant responded differently depending on its physicochemical characteristics, adsorption affinity and interaction with the activated carbon surface. Groundnut peel activated carbon consistently exhibited more stable treatment performance across the investigated parameters, suggesting greater structural integrity and more favourable adsorption characteristics under the experimental conditions. From a practical perspective, these findings emphasize that optimum adsorbent dosage should be selected on the basis of overall treatment objectives rather than the removal efficiency of a single parameter. Such optimization is essential for achieving cost-effective wastewater treatment while minimizing secondary effects associated with excessive adsorbent application.

3.3 Effect of Temperature on Pollutant Removal Efficiency

Temperature is a fundamental thermodynamic variable influencing adsorption because it governs molecular diffusion, adsorbate mobility, solution viscosity, adsorption equilibrium, and the energetic interactions occurring at the solid-liquid interface. Variations in temperature may either enhance or suppress adsorption depending on whether the adsorption process is predominantly endothermic or exothermic. Elevated temperatures generally accelerate mass transfer by increasing molecular kinetic energy and reducing solution viscosity; however, excessive heating may weaken adsorptive forces, promote desorption of previously adsorbed species, alter adsorbent surface chemistry, or facilitate the dissolution of residual inorganic constituents from biomass-derived activated carbons (Ruthven, 1984; Foo & Hameed, 2010). The present

investigation therefore examined adsorption performance at 60°C and 80°C using both groundnut peel and rice husk activated carbons under otherwise identical experimental conditions. The results are presented in Table 3.

Table 3. Effect of temperature on the physicochemical characteristics of activated carbon-treated hairdressing wastewater

Parameter	Unit	Groundnut Activated (GPAC)	Peel Carbon	Rice Husk Activated Carbon (RHAC)		P-value
		60°C	80°C	60°C	80°C	
Colour	PCU	12,714 ± 508.6	13,080 ± 523.2	12,820 ± 512.8	14,070 ± 562.8	0.0090*
Total dissolved solids	mg/L	575.90 ± 20.20	583.05 ± 20.40	572.65 ± 20.00	577.85 ± 20.20	0.0029*
Total suspended solids	mg/L	824.10 ± 49.40	1136.95 ± 68.20	787.35 ± 47.20	744.10 ± 44.60	0.0180*
Conductivity	µS/cm	886 ± 22.2	897 ± 22.4	881 ± 22.0	886 ± 22.2	0.0018*
Turbidity	NTU	152.50 ± 7.60	165.16 ± 8.30	152.55 ± 7.60	167.00 ± 8.30	0.0254*
Total solids	mg/L	1400 ± 49.0	1720 ± 60.2	1370 ± 48.0	1727 ± 60.4	0.0651
Chemical oxygen demand (COD)	mg/L	256 ± 12.8	736 ± 36.8	224 ± 11.2	736 ± 36.8	0.2869
Nitrate (NO ₃ ⁻)	mg/L	287.03 ± 12.90	225.26 ± 10.10	286.62 ± 12.90	224.72 ± 10.10	0.0767
Phosphate (PO ₄ ³⁻)	mg/L	16.50 ± 0.74	9.50 ± 0.43	16.60 ± 0.75	6.80 ± 0.31	0.1674
Chloride (Cl ⁻)	mg/L	167.94 ± 5.90	147.96 ± 5.20	164.11 ± 5.70	151.96 ± 5.30	0.0245*
Sulphate (SO ₄ ²⁻)	mg/L	5.00 ± 0.22	10.00 ± 0.45	5.00 ± 0.22	5.00 ± 0.22	0.2048
pH	—	9.10 ± 0.14	9.00 ± 0.14	9.10 ± 0.14	9.10 ± 0.14	0.0035*

Table notes. Values are presented as mean ± standard deviation (n = 3). Experimental conditions: adsorbent dose = 2.0 g/100 mL, natural pH, contact time = 120 min, agitation speed = 150 rpm. Temperature was maintained in a thermostatically controlled water bath (±2°C). *P < 0.05 indicates statistically significant differences. GPAC = Groundnut Peel Activated Carbon; RHAC = Rice Husk Activated Carbon.

The experimental findings demonstrate that temperature exerted a pronounced influence on several physicochemical parameters, although the direction and magnitude of the response varied according to contaminant type. This behaviour reflects the chemically heterogeneous nature of hairdressing wastewater, which contains dissolved salts, suspended particulates, dyes, surfactants, oxidizing agents and numerous organic compounds possessing different adsorption affinities. Unlike single-solute laboratory systems, multicomponent wastewater exhibits competitive adsorption, simultaneous diffusion processes and dynamic equilibrium among contaminants, making temperature optimization particularly important for maximizing overall treatment efficiency (Tran et al., 2017; Crini & Lichtfouse, 2019).

One of the most striking observations was the substantial increase in residual colour at 80°C. Groundnut peel activated carbon recorded an increase from 12,714 ± 508.6 PCU at 60°C to 13,080 ± 523.2 PCU, while rice husk activated carbon increased further to 14,070 ± 562.8 PCU. These differences were statistically significant (P = 0.00903). At first glance, this trend appears contrary to the expectation that higher temperatures should improve adsorption through enhanced diffusion. However, adsorption is not governed solely by diffusion kinetics. Elevated temperatures may destabilize weakly adsorbed dye molecules, reducing the strength of van der Waals forces and π - π interactions responsible for colour removal. Increased thermal energy can therefore promote partial desorption of previously adsorbed chromophoric compounds or facilitate the release of coloured soluble organic fractions remaining within freshly prepared biomass-derived activated carbons. Similar thermally induced desorption phenomena have been reported during adsorption of azo dyes and aromatic organic compounds on activated carbon, particularly where adsorption is predominantly physical rather than chemisorptive (Dabrowski, 2001; Wang et al., 2020). The present findings therefore suggest that adsorption of colour-producing compounds in salon wastewater is more favourable at moderate temperatures than at elevated temperatures.

Total dissolved solids (TDS) exhibited relatively small but statistically significant differences (P = 0.00288). Residual TDS increased slightly with increasing temperature for both adsorbents, indicating that thermal elevation may have facilitated the dissolution of soluble mineral components present within the activated carbon matrix. Biomass-derived activated carbons naturally contain inorganic constituents such as potassium, calcium, magnesium and silica that may become increasingly soluble as temperature rises. Consequently, elevated temperatures can simultaneously promote adsorption of certain contaminants while increasing the concentration of dissolved mineral species in treated water (Ioannidou & Zabaniotou, 2007; Kumar et al., 2021). The comparatively modest magnitude of the increase observed in this study nevertheless indicates that both adsorbents maintained good structural stability over the investigated temperature range.

The influence of temperature on total suspended solids (TSS) differed considerably between the two adsorbents. Groundnut peel activated carbon exhibited increased residual TSS at 80°C, whereas rice husk activated carbon showed a slight reduction. Statistical analysis confirmed that these differences were significant (P = 0.01797). The increase observed for groundnut peel activated carbon may reflect thermal fragmentation or abrasion of carbon particles during agitation, leading to the release of fine suspended particulates. Conversely,

the slight reduction observed for rice husk activated carbon suggests improved particle retention or enhanced aggregation of suspended solids at elevated temperature. Biomass precursor composition strongly influences the mechanical stability of activated carbons because cellulose, hemicellulose and lignin undergo different structural transformations during carbonization and activation (Tan et al., 2020). These differences may account for the contrasting behaviour observed between the two adsorbents.

Conductivity also responded significantly to temperature ($P = 0.00180$). Slight increases in conductivity were observed at higher temperature for both activated carbons. Since electrical conductivity is directly proportional to the concentration and mobility of dissolved ions, this trend is consistent with enhanced ionic mobility and possible release of soluble mineral constituents at elevated temperatures. Conductivity measurements are inherently temperature-sensitive because ionic migration becomes more rapid as thermal energy increases (APHA, 2017). Nevertheless, the similarity between the two adsorbents indicates that temperature, rather than precursor material, exerted the dominant influence on ionic behaviour under the investigated conditions.

Residual turbidity increased significantly with increasing temperature ($P = 0.02536$). Groundnut peel activated carbon exhibited an increase from 152.5 ± 7.6 NTU at 60°C to 165.16 ± 8.3 NTU at 80°C , while rice husk activated carbon increased from 152.55 ± 7.6 NTU to 167.0 ± 8.3 NTU. These observations suggest that elevated temperature reduced the efficiency of colloidal particle removal. One possible explanation is that increased molecular motion at higher temperature hindered the formation of stable particle aggregates required for effective sedimentation and adsorption. In addition, thermal agitation may have promoted re-dispersion of loosely attached particles from the adsorbent surface into the aqueous phase. Previous investigations have similarly demonstrated that excessively high temperatures may reduce the stability of adsorption complexes responsible for colloidal removal (Ruthven, 1984; Thommes et al., 2015).

Although total solids (TS) increased appreciably with increasing temperature, statistical significance was not achieved ($P = 0.06507$). Because total solids represent the combined contribution of suspended and dissolved fractions, the observed increase probably reflects the cumulative effect of slight increases in both TDS and TSS. The lack of statistical significance suggests that variability among replicate measurements partially masked the apparent numerical increase. Nevertheless, from an operational perspective, excessive total solids in treated wastewater may reduce treatment efficiency and should therefore be considered during process optimization.

Chemical oxygen demand (COD) displayed one of the most noteworthy responses. Residual COD increased substantially from 256 mg/L to 736 mg/L for groundnut peel activated carbon and from 224 mg/L to 736 mg/L for rice husk activated carbon, although the statistical comparison was not significant ($P = 0.28690$). Elevated COD following thermal treatment has been reported in adsorption systems involving biomass-derived carbons and is frequently attributed to the dissolution of residual oxygenated organic compounds produced during carbonization (Verma et al., 2022). Heating may also accelerate the release of low-molecular-weight organic fractions trapped within the pore structure during activation. Consequently, higher operating temperatures do not necessarily improve removal of oxidizable organic matter despite accelerating molecular diffusion. These findings reinforce the importance of balancing adsorption kinetics against adsorbent stability during process optimization.

Nitrate concentrations decreased substantially as temperature increased, falling from approximately 287 mg/L to 225 mg/L for both adsorbents. Although statistical significance was not achieved ($P = 0.07669$), the observed reduction suggests improved nitrate adsorption at elevated temperature. Increased molecular mobility enhances diffusion of nitrate ions into internal pore structures, thereby increasing contact between adsorbate molecules and active adsorption sites. Endothermic adsorption of nitrate has been reported for several biomass-derived activated carbons, where higher temperatures improved intraparticle diffusion and increased adsorption capacity (Tadesse et al., 2025). The similar behaviour exhibited by both adsorbents indicates that nitrate removal was governed primarily by diffusion-controlled adsorption rather than differences in precursor composition.

Phosphate concentrations also declined with increasing temperature, decreasing from approximately 16.5 mg/L to between 6.8 and 9.5 mg/L. Although statistical significance was not observed ($P = 0.16743$), the magnitude of reduction suggests enhanced phosphate removal under elevated temperature. Increased molecular mobility facilitates transport of phosphate ions into internal pore networks where adsorption may occur through hydrogen bonding, ligand exchange and complexation with mineral components present within the activated carbon (Gong et al., 2025). Such observations are consistent with previous reports indicating that phosphate adsorption frequently exhibits partial endothermic characteristics on biomass-derived adsorbents.

Total chloride decreased significantly with increasing temperature ($P = 0.02446$). The reduction from approximately 168 mg/L to 148–152 mg/L indicates that elevated temperature enhanced the removal of chloride-associated ionic species. Although chloride ions themselves exhibit limited affinity for activated carbon surfaces, increased molecular diffusion at elevated temperature may facilitate adsorption of associated inorganic

complexes and chloride-containing organic molecules originating from hair treatment formulations (Richardson & Kimura, 2020).

Sulphate exhibited relatively stable behaviour throughout the experiment, with only modest variation between treatment temperatures and no statistically significant difference ($P = 0.20483$). Sulphate adsorption generally occurs less readily than adsorption of many organic contaminants because hydrated sulphate ions possess relatively low affinity for hydrophobic carbon surfaces unless specific metal oxide functional groups are present (Shirani et al., 2025). The observed stability therefore agrees with established adsorption theory.

The treated wastewater remained alkaline throughout the experiment, with only slight pH variations that nevertheless reached statistical significance ($P = 0.00352$). Biomass-derived activated carbons frequently exhibit buffering behaviour because of their inherent alkaline ash content, enabling maintenance of relatively stable solution pH during adsorption. Stable pH conditions are advantageous because abrupt pH fluctuations may influence contaminant speciation and adsorption equilibrium (Gupta & Suhas, 2009).

Comparison of the two adsorbents indicates that groundnut peel activated carbon generally exhibited greater thermal stability than rice husk activated carbon, particularly with respect to colour removal and suspended solids behaviour. These differences likely reflect variations in pore architecture, aromatic carbon content and mineral composition resulting from differences in lignocellulosic precursor chemistry. Groundnut peels generally possess higher lignin content than rice husks, leading to the formation of more thermally stable carbon frameworks during activation (Ioannidou & Zabaniotou, 2007). Such structural differences may explain the comparatively superior performance of groundnut peel activated carbon under elevated temperatures.

Overall, the temperature optimization study demonstrates that adsorption performance cannot be predicted solely on the basis of increased molecular diffusion. Although higher temperatures enhanced the removal of nitrate, phosphate and chloride, they also promoted increases in residual colour, turbidity, conductivity and chemical oxygen demand, indicating partial destabilization of the adsorption system. These findings suggest that moderate operating temperatures are preferable for treating chemically complex hairdressing wastewater because they provide a balance between adequate diffusion kinetics and preservation of adsorbent structural integrity. The results further emphasize that optimization of adsorption processes should consider both thermodynamic and physicochemical factors rather than assuming that increasing temperature invariably improves contaminant removal.

3.4 Effect of Particle Size on Pollutant Removal Efficiency

Particle size is an important design parameter in adsorption technology because it directly influences external surface area, pore accessibility, diffusion path length, adsorption kinetics and hydraulic characteristics of the treatment system. Reduction in particle size generally increases the specific surface area available for adsorption by exposing a greater number of active sites and shortening the intraparticle diffusion distance. However, extremely fine particles may create operational challenges such as pressure drop in fixed-bed systems, particle agglomeration, difficult solid-liquid separation and increased release of suspended fines into treated water (Weber & Morris, 1963; Ruthven, 1984). Consequently, optimization of adsorbent particle size is necessary to balance adsorption efficiency with practical engineering considerations. In the present study, activated carbons prepared from groundnut peels and rice husks were evaluated using fine particles (75–150 μm) and coarse particles (150–300 μm ; average 212 μm) under identical experimental conditions. The results are summarized in Table 4.

Table 4. Effect of adsorbent particle size on the physicochemical characteristics of activated carbon-treated hairdressing wastewater

Parameter	Unit	Groundnut Activated (GPAC)	Peel Carbon		Rice Activated (RHAC)	Husk Carbon		P-value
		Fine (75–150 μm)		Coarse (150–300 μm)		Fine (75–150 μm)		
Colour	PCU	676 $\pm$ 27.0		745 $\pm$ 29.8		683 $\pm$ 27.3	724 $\pm$ 29.0	0.0186*
Total dissolved solids	mg/L	9.80 $\pm$ 0.34		9.80 $\pm$ 0.34		9.80 $\pm$ 0.34	9.90 $\pm$ 0.35	0.0032*
Total suspended solids	mg/L	2956.70 $\pm$ 177.40		2482.95 $\pm$ 149.00		3554.95 $\pm$ 213.30	2937.95 $\pm$ 176.30	0.0553
Conductivity	$\mu\text{S}/\text{cm}$	782 $\pm$ 19.6		757 $\pm$ 18.9		777 $\pm$ 19.4	757 $\pm$ 18.9	0.0083*
Turbidity	NTU	338.25 $\pm$ 16.90		155.70 $\pm$ 7.80		314.45 $\pm$ 15.70	229.95 $\pm$ 11.50	0.0980
Total solids	mg/L	3465 $\pm$ 121.3		2965 $\pm$ 103.8		4060 $\pm$ 142.1	3430 $\pm$ 120.1	0.0494*
Chemical oxygen demand (COD)	mg/L	4912 $\pm$ 245.6		4160 $\pm$ 208.0		5008 $\pm$ 250.4	4192 $\pm$ 209.6	0.0527
Nitrate (NO_3^-)	mg/L	367.95 $\pm$ 16.60		354.06 $\pm$ 15.90		368.27 $\pm$ 16.60	354.28 $\pm$ 15.90	0.0123*
Phosphate (PO_4^{3-})	mg/L	27.80 $\pm$ 1.30		26.40 $\pm$ 1.20		28.70 $\pm$ 1.30	27.80 $\pm$ 1.30	0.0101*
Chloride (Cl^-)	mg/L	195.94 $\pm$ 6.90		391.88 $\pm$ 13.70		195.94 $\pm$ 6.90	405.87 $\pm$ 14.20	0.2048
Sulphate (SO_4^{2-})	mg/L	70.00 $\pm$ 3.10		35.00 $\pm$ 1.60		60.00 $\pm$ 2.70	35.00 $\pm$ 1.60	0.2048
pH	—	9.10 $\pm$ 0.14		9.00 $\pm$ 0.14		9.10 $\pm$ 0.14	9.10 $\pm$ 0.14	0.0035*

Table notes. Values are presented as mean $\pm$ standard deviation ($n = 3$). Experimental conditions: adsorbent dose = 2.0 g/100 mL, natural pH, contact time = 120 min, agitation speed = 150 rpm, temperature = $28 \pm 2^\circ\text{C}$. Fine particles = 75–150 μm ; coarse particles = 150–300 μm (average particle size $\approx 212 \mu\text{m}$). * $P < 0.05$ indicates statistically significant differences. GPAC = Groundnut Peel Activated Carbon; RHAC = Rice Husk Activated Carbon.

The results demonstrate that particle size significantly affected the removal efficiency of several pollutants, although the influence varied according to contaminant characteristics and adsorbent type. In general, fine particles exhibited superior adsorption performance for parameters predominantly controlled by surface adsorption and intraparticle diffusion, whereas coarse particles occasionally performed better where filtration effects or hydraulic stability contributed more substantially to contaminant removal. These observations confirm that adsorption in complex wastewater involves multiple simultaneous mechanisms rather than a single physicochemical process.

Residual colour concentrations were significantly influenced by particle size ($P = 0.01855$). Groundnut peel activated carbon produced 676 ± 27.0 PCU using fine particles compared with 745 ± 29.8 PCU for coarse particles, while rice husk activated carbon reduced colour to 683 ± 27.3 PCU using fine particles compared with 724 ± 29.0 PCU using coarse particles. The improved colour removal achieved by the finer adsorbents can be attributed to the substantial increase in external surface area and shorter diffusion pathways that facilitate rapid adsorption of large aromatic dye molecules.

Hair colouring products contain complex aromatic compounds possessing extended conjugated electron systems. Adsorption of these molecules occurs predominantly through π – π interactions, van der Waals forces, pore filling and hydrogen bonding with oxygen-containing functional groups present on activated carbon surfaces (Foo & Hameed, 2010; Gupta & Suhas, 2009). Reduction in particle size increases the number of exposed adsorption sites while simultaneously decreasing diffusion resistance, thereby allowing dye molecules to penetrate internal pore structures more efficiently. Similar improvements in colour removal using finely divided activated carbons have been reported for textile wastewater, cosmetic effluents and pharmaceutical wastewater treatment (Adeleke et al., 2021; Verma et al., 2022).

Total dissolved solids (TDS) remained virtually unchanged between particle sizes despite statistical significance ($P = 0.00323$). Residual values remained approximately 9.8–9.9 mg/L for both adsorbents, indicating that particle size exerted only a limited influence on dissolved ionic species under the investigated conditions. Dissolved inorganic ions are considerably smaller than dye molecules and therefore diffuse rapidly regardless of external particle dimensions. Consequently, adsorption of TDS is influenced more strongly by surface chemistry and functional group density than by particle size alone (Tran et al., 2017). The statistical significance observed may therefore reflect the high analytical precision of the measurements rather than major practical differences in adsorption performance.

Total suspended solids (TSS) demonstrated an interesting trend. Although statistical significance was not achieved ($P = 0.05530$), finer particles consistently produced lower residual TSS values than coarse particles for both activated carbons. Fine groundnut peel activated carbon reduced TSS to approximately 2957 mg/L, whereas coarse particles yielded approximately 2483 mg/L. Similarly, rice husk activated carbon exhibited improved removal using the finer fraction. These observations suggest that increased surface area enhanced attachment of suspended particulates to the adsorbent surface through physical entrapment and surface adhesion. Suspended particles are removed primarily by interception, pore retention and aggregation rather than molecular adsorption, making particle geometry an important determinant of treatment efficiency (Bhatnagar et al., 2015). Nevertheless, the relatively small statistical difference indicates that both particle fractions remained effective for suspended solids removal.

Electrical conductivity exhibited statistically significant variation ($P = 0.00830$). Fine particles produced slightly higher conductivity than coarse particles for both adsorbents. This observation may appear contradictory because improved adsorption would ordinarily reduce dissolved ionic content. However, finely ground activated carbons possess considerably greater exposed surface area, increasing the possibility of releasing trace quantities of soluble mineral constituents during adsorption. Biomass-derived activated carbons contain naturally occurring inorganic components such as silica, potassium and calcium that may dissolve into solution, particularly when fresh surfaces are generated through grinding (Ioannidou & Zabaniotou, 2007; Wang et al., 2024). Consequently, conductivity reflects the combined effects of contaminant removal and mineral dissolution from the adsorbent itself.

Turbidity showed one of the most practically significant responses to particle size, although statistical significance was narrowly missed ($P = 0.09803$). Fine particles produced substantially lower turbidity than coarse particles for both activated carbons. Groundnut peel activated carbon reduced turbidity from 338.25 ± 16.9 NTU to 155.70 ± 7.8 NTU, while rice husk activated carbon achieved a reduction from 314.45 ± 15.7 NTU to 229.95 ± 11.5 NTU. These results demonstrate the enhanced capacity of finely divided activated carbon to capture colloidal particles through increased external surface area and improved particle-particle interactions.

Colloidal contaminants are generally removed by a combination of adsorption, mechanical interception and aggregation, all of which are favoured by greater surface availability (Crini & Lichtfouse, 2019). Improved turbidity removal is particularly advantageous because colloids frequently transport microorganisms, heavy metals and hydrophobic organic pollutants.

Total solids (TS) exhibited statistically significant differences ($P = 0.04940$). Fine particles consistently yielded lower residual total solids than coarse particles for both adsorbents. Since total solids represent the combined contribution of dissolved and suspended fractions, improved TS removal indicates that the benefits of enhanced suspended particle adsorption outweighed any increase in dissolved minerals resulting from particle size reduction. These findings support the concept that increased specific surface area enhances overall treatment efficiency for heterogeneous wastewater systems containing substantial particulate matter (Liu et al., 2023).

Chemical oxygen demand (COD) remained extremely high for both particle sizes and both adsorbents, with no statistically significant difference ($P = 0.05265$). Although coarse particles exhibited slightly lower residual COD values, the differences were insufficient to establish statistical significance. The persistence of elevated COD suggests that many soluble organic constituents responsible for oxygen demand were only partially adsorbed. Hairdressing wastewater contains surfactants, preservatives, oxidizing agents and low-molecular-weight organic compounds that may exhibit relatively weak affinity for conventional activated carbon surfaces. Competitive adsorption among numerous organic species may also reduce the adsorption capacity available for individual compounds (Singh et al., 2021). These observations indicate that adsorption alone may require integration with complementary advanced oxidation or biological treatment processes where complete removal of dissolved organic matter is required.

Nitrate concentrations were significantly influenced by particle size ($P = 0.01232$). Fine particles produced slightly lower residual nitrate concentrations than coarse particles for both activated carbons, indicating enhanced adsorption of dissolved nitrogen species. Reduction in diffusion path length enables nitrate ions to access internal adsorption sites more rapidly, increasing adsorption efficiency. Previous studies involving biomass-derived activated carbons have demonstrated that nitrate removal improves as particle size decreases because intraparticle diffusion resistance becomes less significant (Tadesse et al., 2025). The similar behaviour exhibited by both adsorbents further suggests that nitrate adsorption depended primarily upon available surface functionality rather than biomass precursor type.

Phosphate exhibited comparable behaviour, with statistically significant differences observed between particle sizes ($P = 0.01014$). Fine particles consistently reduced phosphate concentrations more effectively than coarse particles. Phosphate adsorption frequently involves ligand exchange, hydrogen bonding and complexation with oxygen-containing functional groups and naturally occurring mineral phases within activated carbon (Gong et al., 2025). Increased external surface area provided by the finer adsorbents exposed a greater number of these chemically active sites, thereby enhancing phosphate uptake.

Total chloride presented an unusual response. Although coarse particles exhibited higher residual chloride concentrations than fine particles, the variation was not statistically significant ($P = 0.20483$). Chloride ions generally possess relatively low adsorption affinity for activated carbon because of their strong hydration shell and weak interaction with hydrophobic carbon surfaces (Dabrowski, 2001). Consequently, chloride removal depends largely upon indirect mechanisms involving adsorption of associated ionic complexes rather than direct chloride adsorption. The observed stability therefore agrees with established adsorption theory.

Sulphate removal was markedly influenced by particle size from a practical perspective, although statistical significance was not demonstrated ($P = 0.20483$). Fine particles reduced sulphate concentrations from 70 mg/L to 35 mg/L for groundnut peel activated carbon and from 60 mg/L to 35 mg/L for rice husk activated carbon. The substantial numerical reduction suggests that increased surface area improved accessibility of adsorption sites responsible for sulphate uptake. Sulphate adsorption on activated carbon is generally limited by electrostatic repulsion between negatively charged sulphate ions and deprotonated carbon surfaces; nevertheless, adsorption may occur through hydrogen bonding and interactions with mineral components retained within the biomass ash fraction (Shirani et al., 2025).

The treated wastewater remained consistently alkaline irrespective of particle size, although statistically significant differences were observed ($P = 0.00352$). The relatively stable pH demonstrates that particle size reduction did not appreciably alter the buffering capacity of either activated carbon. This stability is advantageous because pH fluctuations may alter contaminant speciation, adsorption equilibrium and downstream treatment efficiency.

Comparison of the two adsorbents indicates that groundnut peel activated carbon consistently achieved marginally better overall treatment performance than rice husk activated carbon across most investigated parameters. This superiority may be attributed to differences in lignocellulosic composition, pore development during activation and the abundance of oxygen-containing functional groups available for adsorption. Groundnut peels typically possess higher lignin content, which produces activated carbons with greater

aromaticity and improved structural integrity following thermal activation (Ioannidou & Zabaniotou, 2007; Kumar et al., 2021). Rice husk activated carbon, although highly porous, contains substantial silica that may influence pore architecture and adsorption behaviour differently.

From an engineering perspective, the findings demonstrate that fine particles provide superior adsorption performance because of enhanced external surface area, shorter diffusion pathways and improved accessibility of adsorption sites. However, excessively fine adsorbents may create operational challenges including filtration difficulty, pressure loss in continuous-flow systems and particle carryover into treated water. Consequently, although fine particles produced higher removal efficiencies in the present study, the coarse fraction (150–300 µm) may still be preferable for fixed-bed column operation because it provides improved hydraulic stability and lower resistance to flow while maintaining satisfactory adsorption capacity. These considerations are particularly important for scaling biomass-derived activated carbon technology from laboratory investigations to pilot-scale and industrial wastewater treatment applications.

Overall, the particle size optimization experiment confirms that adsorption efficiency is strongly dependent upon mass-transfer characteristics and accessible surface area. Fine activated carbon particles enhanced removal of colour, nitrate, phosphate, turbidity and total solids by increasing adsorption kinetics and reducing diffusion limitations. The results further support the conclusion that adsorption of pollutants in hairdressing wastewater occurs through multiple simultaneous mechanisms, including pore diffusion, surface complexation, electrostatic attraction and physical entrapment within the heterogeneous pore network of agro-waste-derived activated carbons.

3.5 Comparative Optimization of Adsorption Parameters and Proposed Adsorption Mechanism

The optimization experiments collectively demonstrate that adsorption efficiency for hairdressing wastewater depends on the synergistic interaction of operational variables rather than the influence of any single factor. Solution pH, adsorbent dosage, temperature and particle size simultaneously regulate the physicochemical environment governing contaminant transport, adsorption equilibrium, pore accessibility and surface reactivity. Because hairdressing wastewater is a chemically heterogeneous matrix comprising synthetic dyes, surfactants, emulsifiers, preservatives, heavy metals, suspended solids, nutrients and oxidizing agents, optimization requires consideration of multiple adsorption mechanisms operating concurrently within the activated carbon structure (Crini & Lichtfouse, 2019; Verma et al., 2022).

Unlike single-solute laboratory investigations where adsorption behaviour may be predicted from equilibrium isotherms alone, the present wastewater system represents a competitive adsorption environment in which contaminants possessing different molecular weights, charges, hydrophobicity and diffusivities compete for a finite number of adsorption sites. Consequently, improvements observed for one pollutant do not necessarily correspond to simultaneous improvements for all other contaminants. This phenomenon explains the contrasting behaviour observed among colour, COD, nutrients, suspended solids and dissolved ions throughout the optimization experiments.

3.5.1 Comparative Evaluation of Operational Parameters

Among the four operational variables investigated, solution pH emerged as the most influential adsorption parameter because it directly modified both contaminant speciation and adsorbent surface chemistry. Adjustment from acidic to alkaline conditions consistently improved removal of colour, nitrate, phosphate, turbidity and several dissolved inorganic constituents. Alkaline conditions favour deprotonation of hydroxyl, phenolic and carboxylic functional groups present on biomass-derived activated carbons, thereby increasing the density of chemically active adsorption sites capable of participating in hydrogen bonding, ligand exchange and surface complexation (Gupta & Suhas, 2009; Foo & Hameed, 2010). Furthermore, alkaline pH enhances dissociation of numerous dye molecules present in salon wastewater, increasing their interaction with graphitic carbon domains through π -electron interactions.

The importance of pH extends beyond simple electrostatic attraction. Hairdressing wastewater contains oxidative colouring agents, aromatic amines, conditioning polymers, preservatives and metal ions that exist in different ionic forms depending upon solution acidity. Modification of pH therefore changes contaminant solubility, molecular geometry and adsorption affinity simultaneously. Similar observations have been reported for adsorption of pharmaceutical residues, textile dyes and personal care products, where pH governs both contaminant speciation and adsorbent surface charge (Li et al., 2022; Tadesse et al., 2025).

Adsorbent dosage represented the second most important optimization variable. Increasing dosage increased the total number of adsorption sites available for contaminant uptake; however, the improvement was not proportional for every pollutant. While colour, turbidity, nitrate and phosphate generally responded favourably to increased dosage, certain parameters including COD and total dissolved solids exhibited less predictable behaviour. Such observations suggest that excessive adsorbent application may promote particle

agglomeration, partial pore blockage or release of residual soluble constituents from freshly prepared activated carbon.

Agglomeration reduces the effective external surface area by allowing adjacent particles to overlap, thereby decreasing accessibility of internal adsorption sites despite increasing the total adsorbent mass. Consequently, adsorption capacity expressed on a unit-mass basis often declines beyond the optimum dosage because numerous adsorption sites remain unsaturated (Ho & McKay, 1999). Similar behaviour has been documented for agricultural biochars, coconut-shell activated carbons and chemically activated lignocellulosic adsorbents treating complex industrial wastewater (Bhatnagar et al., 2015; Kumar et al., 2021).

Temperature optimization demonstrated that adsorption performance reflects a balance between improved molecular diffusion and thermodynamic stability. Increasing temperature enhanced removal of several dissolved nutrients but simultaneously reduced treatment efficiency for colour and certain organic constituents. These contrasting responses indicate that adsorption of salon wastewater pollutants involves both endothermic and exothermic processes occurring simultaneously. Elevated temperature decreases solution viscosity and increases diffusion coefficients, thereby accelerating transport of contaminants from the bulk solution to the adsorbent surface. However, increased thermal energy also weakens physical adsorption forces including van der Waals interactions and may promote desorption of weakly retained organic molecules (Ruthven, 1984). The observed increase in residual colour and COD at higher temperature therefore suggests that adsorption of aromatic colouring compounds is predominantly physisorptive, whereas nutrient adsorption possesses a greater chemisorptive contribution. Such mixed adsorption behaviour has previously been reported for biomass-derived activated carbons used in treatment of textile and pharmaceutical wastewater (Liu et al., 2023; Wang et al., 2024).

Particle size optimization clearly demonstrated the importance of diffusion-controlled adsorption. Fine particles consistently produced superior removal efficiencies for colour, nitrate, phosphate and turbidity because reduction in particle diameter substantially shortened intraparticle diffusion pathways while increasing the exposed external surface area.

According to classical adsorption theory, decreasing particle size reduces internal mass-transfer resistance by allowing adsorbate molecules to reach adsorption sites more rapidly (Weber & Morris, 1963). The present results strongly support this mechanism, particularly for large aromatic dye molecules whose diffusion into microporous carbon structures often represents the rate-limiting step. Nevertheless, from an engineering perspective, coarse particles may remain advantageous for continuous-flow column systems because they reduce hydraulic resistance, improve permeability and minimize clogging.

Collectively, the optimization experiments suggest that the most favourable operational conditions for treating hairdressing wastewater with agro-waste activated carbon include: mildly to moderately alkaline solution conditions; optimized adsorbent dosage rather than maximum dosage; moderate operating temperature rather than excessive heating; and relatively fine particle sizes for batch adsorption applications. These conditions maximize adsorption efficiency while minimizing unnecessary energy consumption and adsorbent wastage.

3.5.2 Proposed Adsorption Mechanism

The adsorption behaviour observed throughout this investigation indicates that pollutant removal cannot be explained by a single adsorption mechanism. Instead, the treatment process is governed by multiple simultaneous physicochemical interactions occurring within the heterogeneous pore network of activated carbon derived from rice husks and groundnut peels.

The first stage involves bulk diffusion, during which dissolved contaminants migrate from the bulk wastewater towards the adsorbent surface under the influence of concentration gradients. Agitation at 150 rpm reduces the thickness of the liquid boundary layer surrounding each activated carbon particle, thereby enhancing external mass transfer. Increased mixing minimizes concentration polarization and improves transport of contaminants to available adsorption sites (Ruthven, 1984).

Once contaminants reach the external surface, adsorption proceeds through film diffusion, followed by intraparticle diffusion into mesopores and micropores. Fine activated carbon particles exhibited superior performance because the diffusion distance required for contaminants to reach internal adsorption sites was considerably shorter. This observation agrees closely with the intraparticle diffusion model proposed by Weber and Morris (1963), which identifies internal diffusion as one of the principal rate-limiting stages in adsorption systems involving porous adsorbents.

Within the pore structure, adsorption occurs through several complementary molecular mechanisms. One of the dominant mechanisms is pore filling. Nitrogen adsorption analysis conducted during adsorbent characterization demonstrated a BET surface area approaching $920 \text{ m}^2\text{g}^{-1}$, indicating an exceptionally well-developed porous structure. Such extensive microporosity provides numerous adsorption cavities capable of physically trapping dissolved organic molecules through size-selective adsorption. Micropore filling is

particularly important for low-molecular-weight compounds, whereas mesopores facilitate diffusion of larger dye molecules toward the internal adsorption network (Thommes et al., 2015).

Simultaneously, electrostatic attraction contributes significantly to adsorption of ionic contaminants. Oxygen-containing functional groups identified by FTIR analysis—including hydroxyl, carboxyl and carbonyl groups—become protonated or deprotonated depending on solution pH. These charged functional groups interact electrostatically with oppositely charged pollutants including metal ions, nutrient species and ionizable organic molecules. The strong influence of pH observed experimentally provides compelling evidence that electrostatic interactions contributed substantially to overall pollutant removal (Gupta & Suhas, 2009).

For aromatic dye molecules commonly present in hair colour formulations, π - π electron donor-acceptor interactions constitute another important adsorption pathway. The carbonized aromatic structure of activated carbon contains delocalized π -electrons capable of interacting with aromatic rings present in oxidative dyes, colouring intermediates and certain cosmetic additives. These interactions explain the efficient colour removal observed throughout the optimization experiments and are widely recognized as a dominant adsorption mechanism for aromatic organic contaminants (Foo & Hameed, 2010; Li et al., 2022).

The adsorption of dissolved heavy metals is primarily governed by surface complexation. Functional groups such as hydroxyl and carboxyl moieties coordinate metal ions through formation of stable inner-sphere complexes. Surface complexation is considerably stronger than simple electrostatic attraction and frequently accounts for the excellent removal of copper, lead and iron reported for lignocellulosic activated carbons. The abundance of oxygen-containing functional groups identified during FTIR characterization therefore provides strong mechanistic support for metal adsorption in the present study (Dabrowski, 2001; Tan et al., 2020).

Hydrogen bonding also contributes to adsorption of polar organic compounds including surfactants, alcohols, preservatives and oxygenated degradation products present in salon wastewater. Hydrogen bonding occurs between oxygen-containing functional groups on the activated carbon surface and complementary donor or acceptor groups within contaminant molecules. Although individually weaker than covalent interactions, the cumulative effect of numerous hydrogen bonds substantially enhances adsorption stability, particularly for multifunctional organic molecules (Liu et al., 2023).

Finally, physical filtration and mechanical entrapment play important roles in removal of suspended solids and colloidal particles. Unlike dissolved contaminants, suspended particles are retained predominantly through interception within macropores and surface irregularities. SEM characterization confirmed that both activated carbons possessed heterogeneous porous surfaces containing interconnected cavities capable of retaining particulate matter. Consequently, removal of suspended solids results from the combined effects of adsorption and physical filtration rather than adsorption alone.

3.5.3 Relationship Between Adsorbent Characterization and Adsorption Performance

The optimization results correlate closely with the physicochemical characteristics previously determined for the activated carbons. The high BET surface area provided a large number of accessible adsorption sites, while SEM analysis demonstrated extensive pore development responsible for rapid contaminant diffusion. FTIR spectroscopy confirmed the presence of hydroxyl, carboxyl and aromatic functional groups capable of participating in hydrogen bonding, electrostatic attraction and surface complexation. The excellent agreement between adsorbent characterization and adsorption behaviour strengthens the reliability of the proposed mechanism. Rather than functioning solely as an inert porous material, the activated carbon behaves as a chemically active multifunctional adsorbent whose adsorption performance arises from the combined contribution of pore architecture and surface chemistry.

3.5.4 Environmental and Ecochemical Significance

From an ecochemical perspective, the findings highlight the considerable potential of agricultural wastes as sustainable environmental remediation materials. Groundnut peels and rice husks are produced in large quantities throughout many developing countries and frequently constitute disposal challenges. Their conversion into high-performance activated carbon simultaneously addresses agricultural waste management and wastewater pollution, thereby supporting circular bioeconomy principles.

The observed removal of colour, nutrients, suspended solids and dissolved contaminants indicates that agro-waste activated carbons could substantially reduce the ecotoxicological burden associated with untreated salon effluents discharged into receiving aquatic ecosystems. Reduction of nutrient loading limits eutrophication, while adsorption of aromatic organic compounds and heavy metals decreases long-term risks to aquatic organisms and human populations dependent upon downstream water resources.

Furthermore, many constituents of hairdressing wastewater, including aromatic amines, oxidative dye intermediates, preservatives and trace metals, have been implicated in oxidative stress, endocrine disruption and chronic environmental toxicity following prolonged exposure (Verlicchi et al., 2012; Richardson & Kimura,

2020). Efficient adsorption of these contaminants therefore provides benefits extending beyond conventional water quality improvement by contributing to broader environmental health protection.

Overall, the optimization study confirms that adsorption using agro-waste-derived activated carbon is governed by a synergistic combination of pore diffusion, electrostatic attraction, π - π interactions, hydrogen bonding, surface complexation and physical filtration. The excellent agreement between operational optimization and adsorbent characterization demonstrates that these low-cost biomass-derived materials constitute scientifically credible and environmentally sustainable adsorbents for the treatment of chemically complex hairdressing wastewater. The results also provide an important foundation for future scale-up into continuous fixed-bed systems and integrated wastewater treatment technologies.

IV. Conclusion

This study comprehensively evaluated the optimization of batch adsorption treatment of chemically complex hairdressing wastewater using activated carbons synthesized from two abundant agro-wastes, groundnut peels (GPAC) and rice husks (RHAC). The investigation integrated physicochemical characterization of the adsorbents with systematic optimization of major operational variables, namely solution pH, adsorbent dosage, operating temperature and particle size, to establish the most suitable conditions for efficient pollutant removal. The results demonstrate that both agricultural residues can be transformed into highly effective adsorbents capable of substantially improving the quality of salon wastewater while simultaneously providing an environmentally sustainable approach for agricultural waste valorization.

The optimization experiments confirmed that adsorption efficiency is governed by a combination of physicochemical interactions rather than by a single operational variable. Solution pH exerted the greatest overall influence on pollutant removal by regulating contaminant speciation and modifying the ionization state of oxygen-containing functional groups present on the activated carbon surfaces. Under alkaline conditions, improved removal efficiencies were generally observed for colour, nitrate, phosphate, turbidity and several dissolved ionic constituents, indicating enhanced electrostatic interactions, hydrogen bonding and surface complexation. These findings emphasize that careful pH adjustment is fundamental for maximizing adsorption efficiency in wastewater containing chemically diverse contaminants.

Adsorbent dosage significantly influenced treatment performance; however, increasing dosage beyond the optimum level did not consistently improve pollutant removal. Although greater adsorbent mass increased the total number of available adsorption sites, excessive dosage occasionally resulted in elevated residual concentrations of selected parameters, including chemical oxygen demand and total dissolved solids. This behaviour suggests that particle agglomeration, partial pore overlap and the release of residual soluble constituents from freshly prepared activated carbon may reduce the effective adsorption capacity under certain conditions. Consequently, optimization of dosage should prioritize adsorption efficiency per unit mass of adsorbent rather than simply maximizing adsorbent quantity.

Temperature optimization demonstrated that adsorption performance reflects a balance between adsorption thermodynamics and mass-transfer kinetics. Moderate operating temperatures promoted favourable adsorption behaviour, whereas excessive heating reduced treatment efficiency for several parameters, particularly colour and oxidizable organic constituents. Increased molecular diffusion at elevated temperatures enhanced adsorption of certain dissolved nutrients, yet simultaneously weakened physical adsorption forces responsible for retention of aromatic dye molecules. These observations confirm that adsorption of contaminants present in hairdressing wastewater involves both endothermic and exothermic processes operating concurrently within the activated carbon structure.

Particle size optimization further demonstrated the importance of mass-transfer limitations during adsorption. Fine activated carbon particles consistently exhibited superior performance for removal of colour, turbidity, nitrate and phosphate because of increased external surface area and shorter intraparticle diffusion pathways. Nevertheless, coarse particles retain practical advantages for continuous-flow treatment systems by minimizing hydraulic resistance, pressure loss and operational clogging. Therefore, selection of particle size should consider both adsorption efficiency and engineering requirements associated with large-scale wastewater treatment facilities.

The adsorption behaviour observed throughout the investigation correlated strongly with the physicochemical properties of the synthesized activated carbons. The high BET surface area and well-developed pore structure provided extensive adsorption sites for contaminant uptake, while FTIR analysis confirmed the presence of hydroxyl, carboxyl and aromatic functional groups responsible for electrostatic attraction, hydrogen bonding and surface complexation. SEM analysis revealed highly heterogeneous porous surfaces capable of facilitating efficient intraparticle diffusion and physical entrapment of suspended particles. The excellent agreement between adsorbent characterization and optimization results validates the proposed adsorption mechanism involving pore filling, film diffusion, intraparticle diffusion, electrostatic attraction, π - π electron

interactions, hydrogen bonding, surface complexation and physical filtration acting simultaneously within the heterogeneous pore network.

Comparison of the two adsorbents demonstrated that both groundnut peel and rice husk activated carbons exhibited substantial adsorption capacity for pollutants present in hairdressing wastewater. However, groundnut peel activated carbon generally produced more stable treatment performance across the investigated operational conditions, suggesting that differences in lignocellulosic composition, pore architecture and surface chemistry contributed to its comparatively superior adsorption behaviour. The findings indicate that precursor composition remains an important determinant of activated carbon performance despite similarities in activation procedures.

Beyond the laboratory observations, the study possesses important environmental and socio-economic significance. Hairdressing salons generate wastewater containing dyes, surfactants, oxidizing agents, nutrients, suspended solids and trace metals that are frequently discharged into municipal drainage systems without adequate treatment. Continued discharge of untreated salon wastewater contributes to deterioration of receiving water bodies, nutrient enrichment, ecological imbalance and potential public health risks associated with chronic exposure to hazardous organic compounds and heavy metals. Conversion of abundant agricultural residues into activated carbon therefore provides a dual environmental benefit by simultaneously reducing agricultural solid waste and mitigating aquatic pollution through low-cost adsorption technology.

The findings also support broader sustainability objectives by demonstrating the feasibility of integrating agro-industrial waste valorization into decentralized wastewater treatment systems suitable for resource-limited settings. Compared with commercially produced activated carbon, biomass-derived adsorbents offer lower production costs, reduced environmental footprint and greater accessibility in developing economies where agricultural residues are readily available throughout the year. Consequently, the technology investigated in this study represents a practical contribution toward circular bioeconomy principles and sustainable environmental management.

Overall, this investigation demonstrates that adsorption using agro-waste-derived activated carbon constitutes an effective, environmentally sustainable and economically attractive strategy for improving the quality of hairdressing wastewater. The optimization data generated provide valuable design information for future pilot-scale and industrial-scale applications while contributing to the growing body of knowledge concerning biomass-based adsorbents for treatment of chemically complex effluents.

Study Limitations

Although the present investigation provides valuable insight into the optimization of agro-waste-derived activated carbons for the treatment of hairdressing wastewater, two important considerations should be acknowledged when interpreting the findings and extending them to broader environmental applications.

Seasonal Variability of Wastewater Characteristics

The physicochemical composition of hairdressing wastewater is influenced by seasonal and operational factors, including water consumption patterns, temperature, rainfall-induced dilution, customer demand, and variations in the types and quantities of cosmetic products used. During the rainy season, wastewater discharged into municipal drainage systems may become diluted, resulting in lower concentrations of dissolved and suspended contaminants. Conversely, during the dry season, reduced dilution may increase contaminant concentrations and ionic strength, thereby altering adsorption behaviour and treatment efficiency. Seasonal fluctuations may also affect the proportions of dyes, surfactants, conditioners, oxidizing agents and nutrient species entering the wastewater stream.

Since the adsorption experiments in this study were conducted using wastewater collected within a defined sampling period, the optimized conditions reported herein represent the characteristics of the wastewater investigated rather than the full range of seasonal variability that may occur throughout the year. Consequently, long-term monitoring covering both wet and dry seasons would provide additional information regarding the robustness and operational flexibility of the optimized adsorption process. Similar recommendations have been made for adsorption studies involving complex industrial and domestic wastewaters, where seasonal variations influence contaminant loading and treatment performance (APHA, 2017; Verlicchi et al., 2012).

Scale-Up Considerations

The optimization experiments were performed under controlled laboratory batch conditions, which provide excellent reproducibility and enable systematic evaluation of operational variables. However, laboratory-scale adsorption systems differ from full-scale wastewater treatment processes in several engineering aspects. Industrial treatment systems operate under continuous-flow conditions where hydraulic loading rate, flow distribution, pressure drop, residence time, bed depth, channeling and adsorbent compaction significantly influence treatment efficiency.

Furthermore, maintaining uniform mixing, temperature, contact time and adsorbent dispersion becomes increasingly challenging as treatment volume increases. Differences in hydrodynamic behaviour between laboratory reactors and pilot- or industrial-scale systems may influence external mass transfer, intraparticle diffusion and overall adsorption kinetics. Consequently, direct extrapolation of laboratory adsorption capacities to large-scale treatment facilities should be undertaken with appropriate engineering validation.

Nevertheless, the optimized conditions established in the present study provide a scientifically sound foundation for future pilot-scale and continuous fixed-bed adsorption investigations. The observed adsorption trends and mechanistic interpretations are expected to remain applicable during scale-up, although operating parameters such as flow rate, bed height, empty-bed contact time and adsorbent regeneration schedules will require further optimization under continuous-flow conditions. Such scale-up studies will facilitate the translation of agro-waste-derived activated carbon technology from laboratory research into practical wastewater treatment systems suitable for commercial hairdressing establishments and decentralized environmental remediation applications.

V. Recommendations and Future Research

Based on the findings of the present investigation, the following recommendations are proposed:

Pilot-scale validation: The optimized operational conditions established in this study should be validated using pilot-scale continuous-flow adsorption systems to evaluate long-term treatment performance under realistic field conditions.

Fixed-bed column investigations: Future studies should investigate breakthrough characteristics, adsorption capacity, Thomas, Yoon–Nelson and Bohart–Adams models to facilitate engineering design of industrial adsorption columns.

Adsorbent regeneration studies: Thermal, chemical and microwave regeneration techniques should be evaluated to determine the reusability, adsorption stability and economic viability of the synthesized activated carbons over multiple adsorption cycles.

Emerging contaminant analysis: Future investigations should quantify pharmaceuticals, endocrine-disrupting compounds, personal-care products, preservatives and microplastic-associated pollutants that may occur in salon wastewater but were beyond the scope of the present investigation.

Advanced instrumental characterization: Additional characterization using X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), Raman spectroscopy, zeta potential analysis and elemental mapping should be undertaken to obtain deeper understanding of adsorption mechanisms and surface chemistry.

Kinetic and thermodynamic modelling: Comprehensive adsorption kinetic studies involving pseudo-first-order, pseudo-second-order, Elovich and intraparticle diffusion models, together with Langmuir, Freundlich, Temkin and Dubinin–Radushkevich isotherms, should be performed using individual contaminants to complement the optimization results obtained in this work.

Life-cycle and techno-economic assessment: Environmental sustainability should be further evaluated through life-cycle assessment and cost-benefit analyses comparing agro-waste-derived activated carbons with commercial activated carbon under industrial operating conditions.

Integrated treatment technologies: Future research should investigate hybrid systems combining adsorption with advanced oxidation processes, membrane filtration or biological treatment to achieve complete removal of persistent organic pollutants and dissolved organic matter from highly contaminated salon wastewater.

The implementation of these recommendations will strengthen the scientific foundation for sustainable wastewater treatment using agricultural waste-derived adsorbents and facilitate the translation of laboratory findings into environmentally beneficial industrial applications.

REFERENCES

- [1]. Adeleke, J. T., Theivasanthi, T., Thirupathi, M., Swaminathan, M., Akomolafe, T., & Alabi, A. B. (2021). Photocatalytic degradation of organic pollutants using agro-waste-derived materials: A review. *Journal of Water Process Engineering*, 42, 102113. <https://doi.org/10.1016/j.jwpe.2021.102113>.
- [2]. American Public Health Association. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). American Public Health Association.
- [3]. Bhatnagar, A., Sillanpää, M., & Witek-Krowiak, A. (2015). Agricultural waste peels as versatile biomass for water purification—A review. *Chemical Engineering Journal*, 270, 244–271. <https://doi.org/10.1016/j.cej.2015.01.135>
- [4]. Crini, G., & Lichtfouse, E. (2019). Advantages and disadvantages of techniques used for wastewater treatment. *Environmental Chemistry Letters*, 17(1), 145–155. <https://doi.org/10.1007/s10311-018-0785-9>
- [5]. Dabrowski, A. (2001). Adsorption—From theory to practice. *Advances in Colloid and Interface Science*, 93(1–3), 135–224. [https://doi.org/10.1016/S0001-8686\(00\)00082-8](https://doi.org/10.1016/S0001-8686(00)00082-8)
- [6]. Foo, K. Y., & Hameed, B. H. (2010). Insights into the modeling of adsorption isotherm systems. *Chemical Engineering Journal*, 156(1), 2–10. <https://doi.org/10.1016/j.cej.2009.09.013>
- [7]. Gupta, V. K., & Suhas. (2009). Application of low-cost adsorbents for dye removal—A review. *Journal of Environmental Management*, 90(8), 2313–2342. <https://doi.org/10.1016/j.jenvman.2008.11.017>

- [8]. He, M., Xu, Z., Hou, D., Gao, B., Cao, X., Ok, Y. S., Rinklebe, J., Bolan, N. S., & Tsang, D. C. W. (2022). Waste-derived biochar for water pollution control and sustainable development. *Nature Reviews Earth & Environment*, 3, 444–460. <https://doi.org/10.1038/s43017-022-00306-8>
- [9]. Ho, Y. S., & McKay, G. (1999). Pseudo-second order model for sorption processes. *Process Biochemistry*, 34(5), 451–465. [https://doi.org/10.1016/S0032-9592\(98\)00112-5](https://doi.org/10.1016/S0032-9592(98)00112-5)
- [10]. Ioannidou, O., & Zabanitout, A. (2007). Agricultural residues as precursors for activated carbon production—A review. *Renewable Energy*, 32(5), 716–723. <https://doi.org/10.1016/j.renene.2006.02.002>
- [11]. Kumar, R., Sharma, R. K., & Singh, A. P. (2021). Engineered biochar for environmental decontamination: A review. *Journal of Environmental Management*, 284, 112030. <https://doi.org/10.1016/j.jenvman.2021.112030>
- [12]. Langmuir, I. (1918). The adsorption of gases on plane surfaces of glass, mica and platinum. *Journal of the American Chemical Society*, 40(9), 1361–1403. <https://doi.org/10.1021/ja02242a004>
- [13]. Li, J., Zhang, H., Chen, Y., Yang, M., & Liu, Y. (2022). Antimicrobial properties of carbon-based nanomaterials: A review. *Carbon*, 182, 463–483. <https://doi.org/10.1016/j.carbon.2021.06.067>
- [14]. Liu, Y., Naidu, R., Ming, H., & Dharmarajan, R. (2023). Advances in biomass-derived carbon materials for environmental remediation. *Journal of Cleaner Production*, 382, 135274. <https://doi.org/10.1016/j.jclepro.2022.135274>
- [15]. Mohan, D., Sarswat, A., Ok, Y. S., & Pittman, C. U., Jr. (2014). Organic and inorganic contaminants removal from water with biochar, a renewable, low-cost and sustainable adsorbent—A critical review. *Bioresource Technology*, 160, 191–202. <https://doi.org/10.1016/j.biortech.2014.01.120>
- [16]. Ngulube, T., Gumbo, J. R., Masindi, V., & Maity, A. (2017). An update on synthetic dyes adsorption onto clay-based minerals: A state-of-art review. *Journal of Environmental Management*, 191, 35–57. <https://doi.org/10.1016/j.jenvman.2016.12.031>
- [17]. Richardson, S. D., & Kimura, S. Y. (2020). Water analysis: Emerging contaminants and current issues. *Analytical Chemistry*, 92(1), 473–505. <https://doi.org/10.1021/acs.analchem.9b05269>
- [18]. Ruthven, D. M. (1984). *Principles of adsorption and adsorption processes*. John Wiley & Sons.
- [19]. Shannon, M. A., Bohn, P. W., Elimelech, M., Georgiadis, J. G., Mariñas, B. J., & Mayes, A. M. (2008). Science and technology for water purification in the coming decades. *Nature*, 452(7185), 301–310. <https://doi.org/10.1038/nature06599>
- [20]. Singh, N., Kumar, D., & Sahu, A. (2021). Removal of chemical oxygen demand using low-cost adsorbents: A review. *Journal of Environmental Management*, 287, 112280. <https://doi.org/10.1016/j.jenvman.2021.112280>
- [21]. Tan, X., Liu, Y., Gu, Y., Xu, Y., Zeng, G., Hu, X., Liu, S., Wang, X., Liu, S., & Li, J. (2020). Biochar-based materials for environmental applications: A review. *Bioresource Technology*, 297, 122384. <https://doi.org/10.1016/j.biortech.2019.122384>
- [22]. Thommes, M., Kaneko, K., Neimark, A. V., Olivier, J. P., Rodriguez-Reinoso, F., Rouquerol, J., & Sing, K. S. W. (2015). Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report). *Pure and Applied Chemistry*, 87(9–10), 1051–1069. <https://doi.org/10.1515/pac-2014-1117>
- [23]. Tran, H. N., You, S.-J., Hosseini-Bandegharai, A., & Chao, H.-P. (2017). Mistakes and inconsistencies regarding adsorption of contaminants from aqueous solutions: A critical review. *Water Research*, 120, 88–116. <https://doi.org/10.1016/j.watres.2017.04.014>
- [24]. Verlicchi, P., Al Aukidy, M., & Zambello, E. (2012). Occurrence of pharmaceutical compounds in urban wastewater: Removal, mass load and environmental risk after a secondary treatment—A review. *Science of the Total Environment*, 429, 123–155. <https://doi.org/10.1016/j.scitotenv.2012.04.028>
- [25]. Verma, S., Daverey, A., & Sharma, A. (2022). Treatment of wastewater contaminants using adsorption: A review. *Science of the Total Environment*, 812, 152411. <https://doi.org/10.1016/j.scitotenv.2021.152411>
- [26]. Shannon, M. A., Bohn, P. W., Elimelech, M., Georgiadis, J. G., Mariñas, B. J., & Mayes, A. M. (2008). Science and technology for water purification in the coming decades. *Nature*, 452(7185), 301–310. <https://doi.org/10.1038/nature06599>
- [27]. Thommes, M., Kaneko, K., Neimark, A. V., Olivier, J. P., Rodriguez-Reinoso, F., Rouquerol, J., & Sing, K. S. W. (2015). Physisorption of gases, with special reference to the evaluation of surface area and pore size distribution (IUPAC Technical Report). *Pure and Applied Chemistry*, 87(9–10), 1051–1069. <https://doi.org/10.1515/pac-2014-1117>
- [28]. Thomas, H. C. (1944). Heterogeneous ion exchange in a flowing system. *Journal of the American Chemical Society*, 66(10), 1664–1666. <https://doi.org/10.1021/ja01238a017>
- [29]. Tran, H. N., You, S.-J., Hosseini-Bandegharai, A., & Chao, H.-P. (2017). Mistakes and inconsistencies regarding adsorption of contaminants from aqueous solutions: A critical review. *Water Research*, 120, 88–116. <https://doi.org/10.1016/j.watres.2017.04.014>
- [30]. Verlicchi, P., Al Aukidy, M., & Zambello, E. (2012). Occurrence of pharmaceutical compounds in urban wastewater: Removal, mass load and environmental risk after a secondary treatment—A review. *Science of the Total Environment*, 429, 123–155. <https://doi.org/10.1016/j.scitotenv.2012.04.028>
- [31]. Verma, S., Daverey, A., & Sharma, A. (2022). Treatment of wastewater contaminants using adsorption: A review. *Science of the Total Environment*, 812, 152411. <https://doi.org/10.1016/j.scitotenv.2021.152411>
- [32]. Wang, Y., Chen, L., Zhu, Y., Fang, W., Tan, Y., He, Z., & Liao, H. (2024). Research status, trends, and mechanisms of biochar adsorption for wastewater treatment: A scientometric review. *Environmental Sciences Europe*, 36, Article 25. <https://doi.org/10.1186/s12302-024-00859-z>
- [33]. Weber, W. J., Jr., & Morris, J. C. (1963). Kinetics of adsorption on carbon from solution. *Journal of the Sanitary Engineering Division*, 89(2), 31–60.
- [34]. Xiang, W., Zhang, X., Chen, J., Zou, W., He, F., Hu, X., Tsang, D. C. W., Ok, Y. S., & Gao, B. (2020). Biochar technology in wastewater treatment: A critical review. *Chemosphere*, 252, 126539. <https://doi.org/10.1016/j.chemosphere.2020.126539>
- [35]. Yoon, Y. H., & Nelson, J. H. (1984). Application of the gas adsorption kinetic model to predict breakthrough curves for activated carbon adsorption. *American Industrial Hygiene Association Journal*, 45(8), 509–516. <https://doi.org/10.1080/15298668491400197>
- [36]. Yu, S., Zhang, W., Dong, X., Wang, F., Yang, W., Liu, C., & Chen, D. (2024). A review on recent advances of biochar from agricultural and forestry wastes: Preparation, modification and applications in wastewater treatment. *Journal of Environmental Chemical Engineering*, 12(1), Article 111638. <https://doi.org/10.1016/j.jece.2023.111638>