International Journal of Engineering & Artificial Intelligence Art Design

IJEAIAD Vol. 1, No. 2 (2025) pp. 31-46

Sustainable Treatment of Industrial Wastewater Using Orange Peel-Based Activated Carbon: Adsorption of Contaminants and COD Reduction

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ARTICLE INFO

Article history:
Received 25 August 2025 Revised 13 September 2025 Accepted 17 September 2025 Available online 18 September 2025

Keywords:
Activated Carbon, Industrial Wastewater Treatment, Contaminant Removal, Adsorption Technology, COD Reduction.

ABSTRACT

Industrial wastewater contains toxic organic and inorganic pollutants, posing significant environmental risks. Adsorption using activated carbon is an effective, simple, and scalable treatment method. This study investigates Orange Peel-derived activated carbon (OPAC) as a sustainable, low-cost adsorbent for chemical oxygen demand (COD) removal from industrial effluents. OPAC exhibited a high surface area of 510.4 m^2/g, with FTIR, SEM, and XRD analyses confirming its porous structure and abundant functional groups. Adsorption was strongly influenced by pH, achieving maximum capacity of 464 mg/g and COD removal of 92.8% at pH 6. Optimal performance was observed at 30 °C, with higher temperatures reducing efficiency. Adsorbent dose and contact time were critical, with maximum COD reduction of 96.6% and equilibrium capacity of 484 mg/g at 3 g/L and 45 minutes, respectively. Agitation speed at 200 rpm further enhanced adsorption, yielding 484 mg/g capacity and 96.8% COD removal. Comparative analysis showed that OPAC outperformed commercial activated carbon in both adsorption capacity and COD reduction. Utilizing orange peel, an abundant agricultural waste, for activated carbon production promotes efficient wastewater treatment and resource valorization. Overall, OPAC demonstrates significant potential as an eco-friendly, cost-effective adsorbent for industrial wastewater treatment.

1. Introduction

Rapid industrial growth and urban development over recent decades have significantly increased both the quantity and complexity of wastewater discharged into water bodies[1–3]. Industrial effluents often contain diverse hazardous pollutants, including heavy metals, synthetic dyes, phenolic compounds, hydrocarbons, and pharmaceutical residues[4–6]. These contaminants are typically toxic, non-biodegradable, and chemically stable, rendering them persistent in the environment and challenging to remove using conventional treatment methods. Inadequate treatment of industrial wastewater can lead to serious environmental and public health issues, such as bioaccumulation in the food chain, eutrophication of aquatic ecosystems, and adverse effects including carcinogenicity, mutagenicity, and endocrine disruption[7], [8]. Consequently, the increasing stringency of wastewater discharge regulations highlights the urgent need for advanced, cost-effective, and sustainable treatment technologies.

Conventional techniques, such as coagulation flocculation, chemical precipitation, ion exchange, membrane filtration, ozonation, electrochemical processes, and advanced oxidation methods, have been widely used for pollutant removal[9], [10]. Despite their effectiveness, these approaches are often Despite their effectiveness, these methods often involve high operational costs, complex infrastructure, reliance on skilled labor, and the generation of secondary wastes such as sludge, posing additional disposal challenges. This has driven growing interest in sustainable, economically feasible, and environmentally friendly alternatives, among which adsorption has emerged as particularly promising. Adsorption is recognized for its operational simplicity, high efficiency, scalability, and low energy requirements, while avoiding the production of hazardous by-products[11–13].

Activated carbon (AC) has been extensively studied and applied for wastewater treatment due to its exceptional physicochemical properties, including high surface area, well-developed porosity, and abundant surface functional groups[14–18].

Commercial activated carbon (CAC), derived from carbon-rich precursors such as coal, wood, or coconut shells, is highly effective for removing a wide range of contaminants, including organic compounds (dyes, phenols, pharmaceuticals) and inorganic species (lead, cadmium, chromium), with adsorption capacities often exceeding 200 mg/g under optimized conditions[19]–[26]. However, the high cost of CAC limits its accessibility, particularly in developing countries, motivating the search for low-cost, sustainable alternatives from agricultural residues and industrial by-products.

Orange Peels, an abundant agro-industrial waste, have attracted attention as a promising precursor for activated carbon production[26–32]. Orange Peel-based activated carbon (OPAC) offers advantages such as low cost, availability, and sustainability, while supporting waste valorisation. Rich in cellulose and lignin, Orange Peels can be converted into highly porous AC with large surface area and abundant functional groups. Several studies have demonstrated the effectiveness of OPAC for removing heavy metals, dyes, and pharmaceutical residues. For instance, Chaudhary et al. (2020) reported maximum adsorption capacities of 150 mg/g for lead and 120 mg/g for cadmium[33], while Patel et al. (2019) highlighted excellent methylene blue removal under acidic conditions[34]. Other studies confirmed OPAC's versatility for pharmaceutical pollutant removal, such as ibuprofen and paracetamol[35].

The adsorption performance of OPAC is influenced by key process parameters, including pH, temperature, adsorbent dosage, contact time, and agitation speed[36], [37]. Acidic conditions generally enhance adsorption due to increased electrostatic interactions between the adsorbent and pollutants, whereas temperature affects molecular mobility and diffusion into the adsorbent's pores. Optimal adsorbent dosage, contact time, and agitation speed further improve efficiency depending on contaminant type and wastewater characteristics. Characterization techniques such as FTIR, SEM, and XRD are critical for understanding OPAC's surface functional groups, morphology, and crystallinity, which directly influence adsorption capacity [38–40].

In addition to performance, OPAC represents a sustainable alternative to conventional AC, as it utilizes renewable, low-cost agricultural waste. This approach aligns with the principles of the circular economy by converting agro-industrial by-products into valuable adsorbents, reducing reliance on non-renewable resources, and supporting global sustainability goals[41–43]. This study aims to evaluate the adsorption efficiency of OPAC for industrial wastewater treatment under varying physicochemical conditions. Experimental parameters investigated include pH (2–8), temperature (30–60 °C), adsorbent dosage (0.01–0.1 g/L), contact time (10–60 min), and agitation speed (300–600 rpm). The findings provide insight into optimal operational conditions for pollutant removal using OPAC, offering a cost-effective, eco-friendly solution for industrial wastewater treatment and contributing to Sustainable Development Goals[44] (SDG 6, SDG 12, and SDG 13) by promoting environmentally responsible and economically viable technologies.

2. Material and methods

2.1. Preparation of the Orange Peel-Based Activated Carbon

The Orange Peel-based activated carbon (OPAC) was prepared through a two-step process involving carbonization and chemical activation. Initially, raw Orange Peels (as shown in **Fig. 1**) were washed, dried, and ground into fine powder. The powdered biomass was then carbonized in a tubular furnace under a nitrogen atmosphere at 500°C for 2 hours. The resulting char was chemically activated by soaking in phosphoric acid (1:1 w/w) for 24 hours, followed by drying at 100°C. Final activation was performed at 800°C for 1.5 hours to enhance the adsorbent's porosity and surface area. The activated carbon was thoroughly washed to remove residual chemicals and dried at 110°C. As illustrated in **Fig. 1**, the prepared activated carbon was then introduced into a batch adsorption system containing industrial wastewater sourced from the Rockat Fertilizer Factory in New Salhia, Sharqia, Egypt using a magnetic stirrer with a hot plate to facilitate mixing. After sufficient contact time, the treated effluent was filtered, resulting in a notable reduction in chemical oxygen demand (COD). The OPAC was characterized by FTIR, SEM, XRD, and BET analyses to assess its surface morphology, functional groups, crystallinity, and surface area. For comparison, commercial activated carbon was procured from a local supplier in Cairo, Egypt, as outlined in Table 1.

Table 1. Company and molecular weight for materials used.

No	Materials	company
1	Industrial wastewater	Rockat fertilizer factory in new salhia, sharqia, Egypt
2	Orange Peel	Local market, cairo ,Egypt

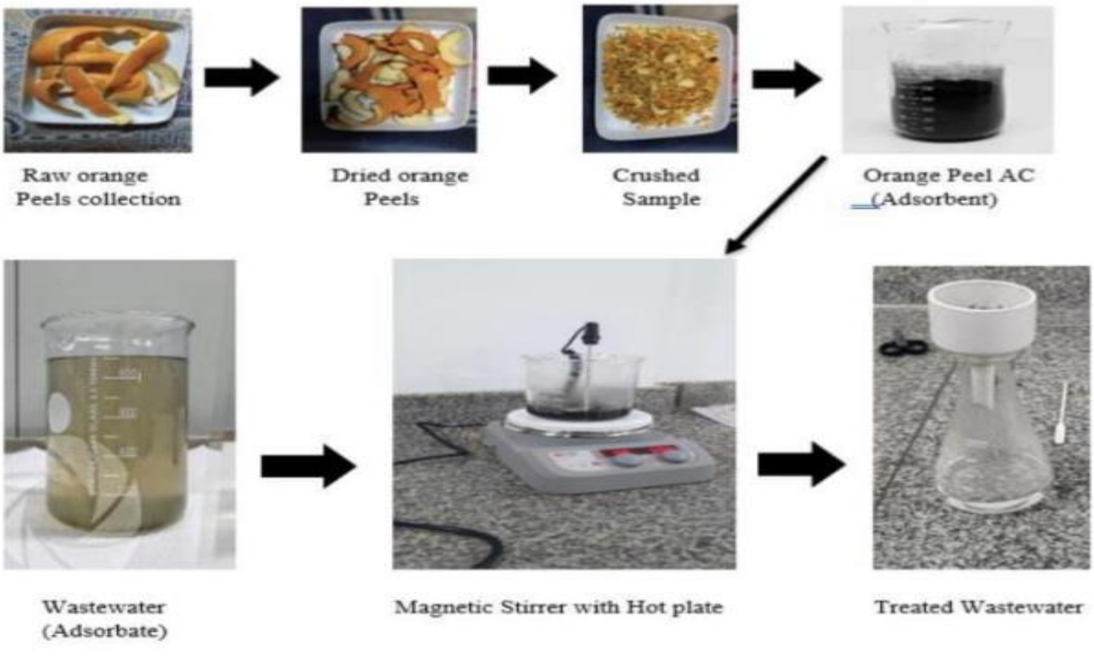

Fig. 1. Schematic of OPAC Synthesis and Wastewater Treatment Process.

2.2. Optimization of the Adsorption Parameters

In this investigation, Orange Peel-based activated carbon (OPAC) was employed to adsorb contaminants and reduce COD in industrial wastewater. The adsorption process was analyzed under the influence of five different parameters: pH, duration of contact, adsorbent dosage, temperature, and agitation speed.

2.2.1. Batch Adsorption Experiments

All experiments in this study were conducted in batch mode at ambient room temperature to maintain procedural simplicity, reproducibility, and ease of operation. Batch mode was selected for its suitability in preliminary adsorption studies and its ability to control experimental variables precisely. The adsorption experiments were performed in 250 mL borosilicate Erlenmeyer flasks, each containing a predetermined volume of industrial wastewater obtained from the Rockat fertilizer factory in New Salhia, Sharqia, Egypt (as detailed in Table 1). Orange Peel-based activated carbon (OPAC), prepared through a two-step process involving carbonization and chemical activation, was used as the adsorbent for all tests.

Before each experiment, a fixed dosage of OPAC was weighed and added to the respective flasks. The flasks were placed on an orbital shaker and agitated at controlled speeds (ranging from 300 to 600 rpm) to maintain uniform suspension and ensure consistent contact between the adsorbent and contaminants. The pH of each wastewater sample was adjusted to the desired value (ranging from 2 to 8) using dilute NaOH or HCl solutions, and the pH was verified with a calibrated pH meter before the start of each test. After adjusting the pH, a known volume of the wastewater was added to the flask containing the OPAC, and the adsorption process was initiated by continuous shaking. At predetermined contact times (ranging from 10 to 60 minutes), individual flasks were removed from the shaker. The mixtures were then filtered using Whatman No. 44 filter paper to separate the spent adsorbent from the treated solution. The filtered samples were analyzed to evaluate the concentration of contaminants remaining in the solution, allowing the assessment of adsorption efficiency under various operational parameters, including contact time, adsorbent dosage (0.01 to 0.1 g/L), temperature (30 to 60°C), and agitation speed. All tests were performed in duplicate to ensure data reliability, and average values were used for subsequent analysis.

The equations below were used to determine the COD Reduction (%) and the equilibrium adsorption capacity.

$$\%COD\ Reduction = (COD_o - COD_e)/\ COD_o \times 100 \quad \textbf{Eq.1}$$

$$Q_e = (CODo - COD_e) \times V/W \quad \textbf{Eq.2}$$

For example, the initial and equilibrium COD concentrations (mg/L), are shown as $CODo$ and COD_e (ppm). The dried adsorbent used during the experiment weighs W (g), while V (mL) is the volume of solution containing contaminates. Q_e (mg/g) is the solid's equilibrium adsorption capacity.

2.3. Testing Procedures

2.3.1. Characterization of OPAC

The Orange Peel-based activated carbon (OPAC) was characterized using several analytical techniques to assess its structural, morphological, and surface properties. The specific surface area and porosity of OPAC were determined through Brunauer-Emmett-Teller (BET) analysis, which provided insights into its adsorption potential. Fourier Transform Infrared Spectroscopy (FTIR) was employed to identify functional groups such as hydroxyl, carboxyl, and carbonyl groups on the surface of OPAC, which are crucial for contaminant adsorption. Scanning Electron Microscopy (SEM) imaging revealed the surface morphology, pore structure, and texture of OPAC, while X-ray Diffraction (XRD) analysis was used to evaluate its crystallinity and phase composition. These characterization methods collectively provided a comprehensive understanding of OPAC's properties, confirming its suitability as an effective adsorbent for industrial wastewater treatment.

2.3.2. Collection and Composition of Industrial Wastewater

A sample of industrial wastewater was collected from a local juice processing factory in Cairo, Egypt, and used for the experimental investigation in this study. The key physicochemical characteristics of the wastewater, including chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS), pH, and color, are summarized in Table 2. The COD was 250 mg/L, indicating a relatively low concentration of organic pollutants compared to more heavily contaminated effluents, such as those from fertilizer or chemical industries. The TDS and TSS values were 180 mg/L and 320 mg/L, respectively, reflecting the moderate levels of dissolved and suspended substances typically found in food-industry effluents. The wastewater exhibited a slightly acidic pH of 5.8 and a light-yellow color, characteristic of fruit juice residues. pH adjustments were made using 0.1 M NaOH or 0.1 M HCl, as required for batch adsorption experiments. To ensure reproducibility, all experiments were conducted in triplicate, and variations due to potential seasonal or source-based changes in wastewater composition were monitored. All chemicals and reagents used were of analytical grade and obtained from local sources. This characterization provides the baseline for assessing the adsorption performance of Orange peel–based activated carbon (OPAC) in treating food-industry wastewater.

Table 2. The characteristics of the industrial's wastewater.

Colour	PH	TSS, (ppm)	COD, (ppm)	TDS, (ppm)	Alk
light-yellow	5.8	320	250	180	0

2.3.3. Analysis of Raw and Treated Water

The pH of both raw and treated wastewater samples was measured using a pH meter (AD1000). Total Suspended Solids (TSS) and Total Dissolved Solids (TDS) concentrations were analyzed according to standard procedures. Additionally, the Chemical Oxygen Demand (COD) was determined using a standard analytical method to assess the organic pollutant load. All analyses were carried out using high-precision instruments, with pH adjustments made using 0.1 M NaOH or HCl, depending on the experimental conditions. For the analysis of other parameters, such as metal ion concentrations, atomic absorption spectroscopy (AAS) was employed, utilizing the ZEEnitu 700P-Analytik Jena-Germany flammatic absorption spectrometer. This method ensured precise and reliable detection of contaminants. These analytical procedures provided a comprehensive assessment of the wastewater's physicochemical characteristics, forming a solid foundation for evaluating the effectiveness of Orange Peel-based activated carbon (OPAC) in wastewater treatment.

3. Results and discussion

3.1. Characterization of Activated Carbon:

3.1.1. FTIR spectroscopy.

Fourier-transform infrared (FTIR) spectroscopy is a powerful analytical technique widely employed to identify functional groups on the surface of porous materials, such as activated carbon. These surface functional groups play a pivotal role in adsorption mechanisms, significantly influencing the material's interaction with various contaminants. In the context of biomass-derived activated carbon, FTIR analysis offers valuable insights into the chemical structure and surface chemistry, which directly correlate with its adsorption performance.

The FTIR spectrum of Orange Peel-based activated carbon prepared at an activation temperature of 800 °C. The spectrum reveals the presence of several characteristic absorption bands corresponding to key functional groups. Notable peaks typically include those associated with hydroxyl (–OH), carboxyl (–COOH), carbonyl (C=O), and aromatic C=C stretching vibrations. These groups are known to enhance the adsorptive interaction between the activated carbon surface and pollutant molecules, thereby contributing to the material's high adsorption efficiency.

The presence and intensity of these peaks confirm the successful development of surface functionalities during the carbonization and activation processes. Consequently, FTIR spectroscopy not only verifies the chemical nature of the functional groups but also supports the evaluation of the material's suitability for environmental remediation applications.

A summary of the major functional groups commonly observed in FTIR analysis of activated carbon, along with their associated wavenumbers and vibration types, is presented in Table 3.

Table 3. Major FTIR Peaks Observed in Orange Peel-Based Activated Carbon.

Wavenumber (cm^{-1})	Functional Group	Vibration Type	Description
~3400	–OH (hydroxyl groups)	O–H stretching	Indicative of alcohols, phenols, and adsorbed water
~2920	$–CH_2$ / $–CH_3$	C–H stretching	Aliphatic chains (possible remnants of biomass)
~1700	C=O (carbonyl groups)	C=O stretching	Associated with carboxylic acids, ketones, and aldehydes
~1600	C=C (aromatic rings)	C=C stretching	Suggests the presence of aromatic structures formed during carbonization
~1400	$–COO^-$ (carboxylates)	C–O symmetric stretching	Indicative of carboxylic acids or their salts
~1100–1000	C–O–C or C–O	C–O stretching	Often linked to alcohols, ethers, or esters

3.1.2. XRD results.

The crystalline nature of the activated carbon produced from Orange Peel was examined using X-ray diffraction (XRD) analysis. The XRD patterns provided insight into the structural changes induced during the activation process. A clear diffraction peak observed at $2\theta \approx 25°$ is characteristic of the graphitic (002) plane, confirming the formation of an ordered carbon structure in the activated carbon. The absence of sharp diffraction peaks in the lower-angle regions suggests a reduction in crystallinity, which is typical for activated carbon materials. These findings align with similar studies where the activation process led to an increase in amorphous carbon content, enhancing the material's porosity. The observed peak positions and intensities further corroborate the effectiveness of the activation method used in developing a highly porous and structurally modified carbon material. A summary of the main diffraction features and their corresponding interpretations is presented in **Table 4** and **Fig.2**.

Table 4. Summary of XRD Findings for Orange Peel-Based Activated Carbon.

2θ Position (°)	Corresponding Plane	Observation	Interpretation
≈ 25°	(002)	Broad diffraction peak	Indicates partial graphitization and formation of layered carbon structures

< 20°	—	Absence or low-intensity peaks	Suggests reduced crystallinity and dominance of amorphous carbon
Broad background hump	—	Wide, low-intensity region across 20°–30°	Characteristic of amorphous carbon with disordered structure
No sharp peaks	—	Lack of crystalline phases	Confirms thermal degradation and structural transformation into amorphous carbon

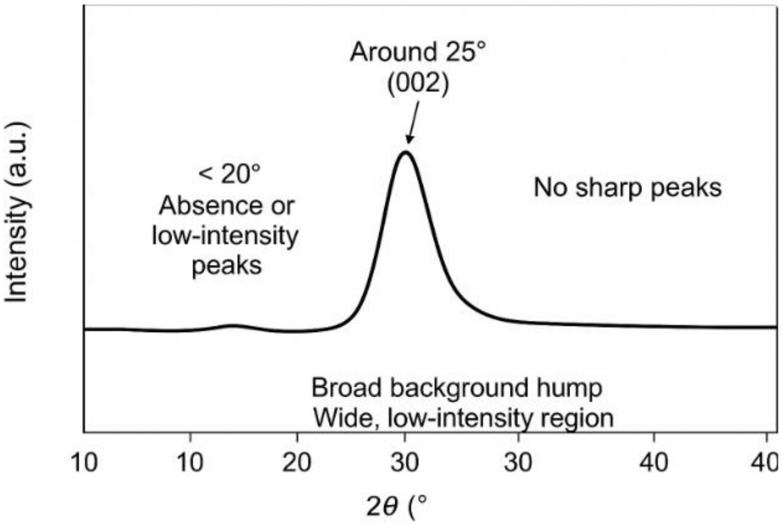

Fig.2. XRD Pattern of Orange Peel-Derived Activated Carbon Showing Amorphous Carbon Structure and Partial Graphitization.

3.1.3. Scanning electron microscopy (SEM).

The surface morphology of the Orange Peel-derived activated carbon was investigated using scanning electron microscopy (SEM) as shown in **Fig.3**. The SEM images revealed significant changes in the surface structure before and after activation. Raw Orange Peels exhibited a smooth and compact surface with minimal porosity, characteristic of the native biomass. However, after activation at 800°C, the surface of the activated carbon was markedly altered, showing the development of a highly porous and rough texture. The presence of well-defined pores and irregular cavities indicates the successful activation and the formation of a high surface area, which is crucial for enhancing adsorption capacity. These structural modifications, as observed under SEM, align with the increase in adsorption performance reported in the FTIR and other characterization studies, confirming the effectiveness of the activation process in improving the material’s adsorptive properties.

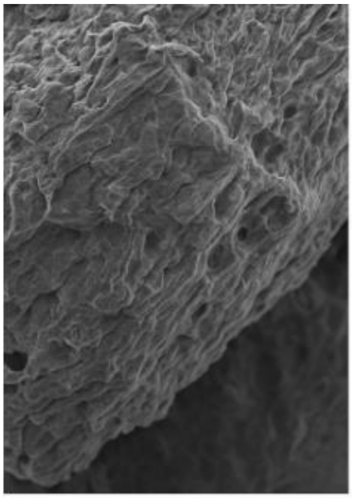

Fig. 3. SEM micrographs at 2000× of magnification for the activated carbon (OPAC).

3.2. Batch Adsorbent

3.2.1. Effect of pH

The effect of pH on the adsorption capacity and COD reduction efficiency of Orange Peel-derived activated carbon (OPAC) was investigated over a pH range of 4 to 10. The adsorption capacity (mg/g) was determined based on the number of COD adsorbed per gram of adsorbent, while COD reduction (%) was calculated from the initial and equilibrium concentrations of COD in solution. The results, shown in **Fig. 4**, indicate that pH plays a crucial role in the adsorption performance of OPAC.

At pH 6, the OPAC exhibited the highest adsorption capacity of 464 mg/g and achieved a COD reduction of 92.8%, indicating optimal interaction between the surface of the activated carbon and organic pollutants under slightly acidic conditions. At pH 8, the capacity dropped slightly to 408 mg/g, with a COD reduction of 81.6%. Similarly, at pH 4, although the adsorption capacity was still relatively high (400 mg/g), the COD reduction was only 80%. At pH 10, both adsorption capacity (390 mg/g) and COD reduction (78%) declined, suggesting reduced efficiency in alkaline environments.

These results clearly demonstrate that the adsorption process is highly sensitive to the solution pH, with optimal performance observed at pH 6. The enhanced adsorption under slightly acidic conditions may be attributed to favorable surface charge interactions and increased availability of active functional groups on the OPAC surface for binding organic pollutants.

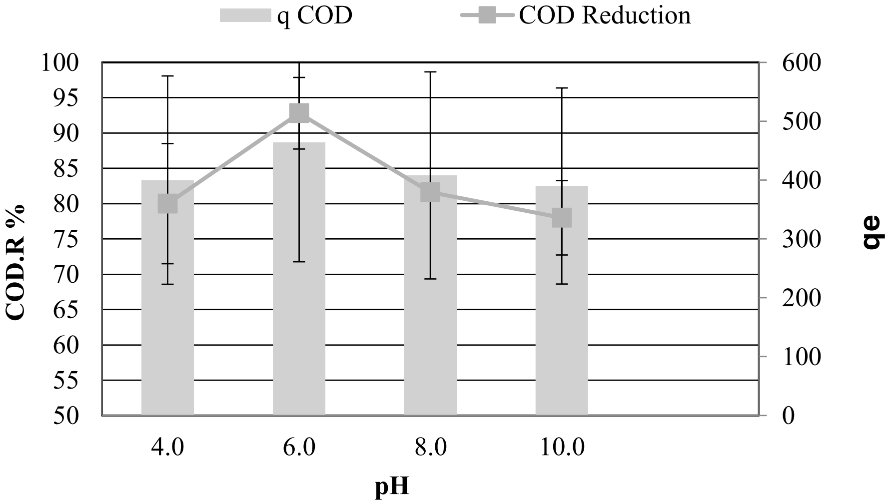

Fig. 4. Effect pH on COD removal efficiency and the adsorption capacity of COD at adsorbent dose =0.5g/l, contact time=30 min, and agitation speed= 200 rpm at 30 ^{0}C.

3.2.2. Effect of temperature

Temperature is a critical factor influencing the adsorption process, as it affects the mobility of adsorbate molecules, surface interactions, and the structural behavior of the adsorbent. To evaluate the effect of temperature on the adsorption performance of Orange Peel-derived activated carbon (OPAC), experiments were conducted at 30°C, 40°C, 50°C, and 60°C. The results, shown in **Fig. 5**, reveal that increasing temperature led to a gradual decline in both adsorption capacity and COD reduction efficiency.

At 30°C, the OPAC exhibited the highest adsorption capacity of 464 mg/g and achieved a COD reduction of 92.8%, indicating highly favorable adsorption conditions at moderate temperatures. As the temperature increased to 40°C, the adsorption capacity decreased to 440 mg/g, with COD reduction dropping to 88%. Further increases in temperature to 50°C and 60°C led to additional reductions in capacity (422 mg/g and 410 mg/g, respectively), accompanied by COD reduction efficiencies of 84.4% and 82%.

These results suggest that the adsorption process is exothermic, as higher temperatures negatively impacted the adsorption performance. The decline in efficiency at elevated temperatures may be attributed to increased molecular motion, which can weaken the physical interactions between adsorbate molecules and active sites on the adsorbent surface, or even cause partial desorption. Thus, 30°C appears to be the optimal temperature for maximum adsorption efficiency, reinforcing the suitability of OPAC for use under ambient or slightly warm conditions in environmental applications.

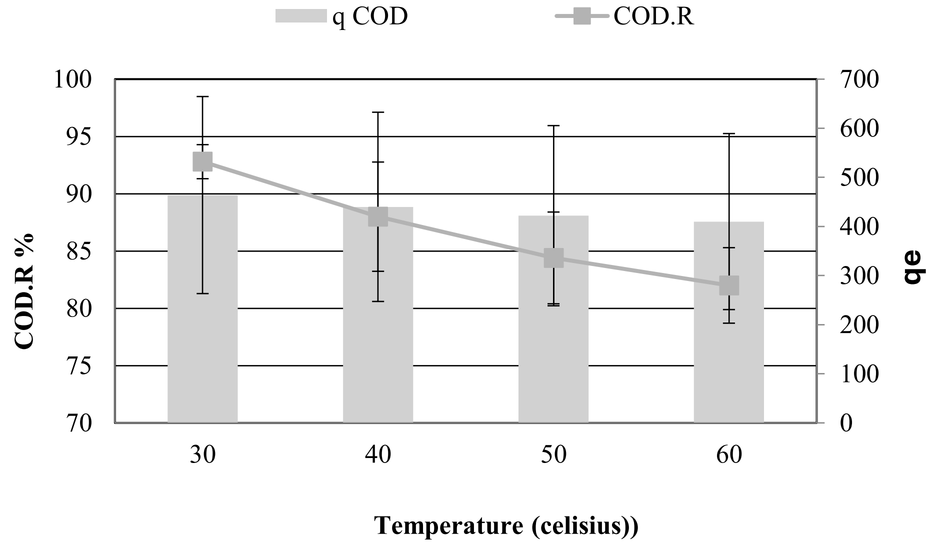

Fig. 5. Effect of temperature on COD removal efficiency and the adsorption capacity of COD at adsorbent dose =0.5 g, contact time=30 min, pH = 6, and agitation speed=200 rpm.

3.2.3. Effect of adsorbent dose

The adsorbent dose is a key factor influencing the performance of the adsorption process, as it determines the availability of active sites for contaminant removal. In this study, the effect of Orange Peel-derived activated carbon (OPAC) dosage on the adsorption of organic pollutants was assessed by varying the dose from 0.5 g/L to 3 g/L, while maintaining constant initial contaminant concentrations.

As shown in **Fig. 6**, increasing the adsorbent dose resulted in a significant enhancement in COD reduction, reaching 95.2% at 1 g/L, and up to 96.6% at 3 g/L. This improvement can be attributed to the higher number of available adsorption sites with increasing OPAC dose, which facilitates greater pollutant uptake from the solution.

However, a decrease in adsorption capacity (mg/g) was observed as the dose increased. For instance, the adsorption capacity declined from 464 mg/g at 0.5 g/L to 80.5 mg/g at 3 g/L. This inverse relationship occurs because, while more active sites are available at higher doses, the fixed amount of contaminant becomes distributed across a larger mass of adsorbent, resulting in a lower calculated uptake per gram of adsorbent.

These findings highlight that although higher doses improve removal efficiency, the adsorption capacity per unit mass decreases, and therefore, an optimal balance between removal efficiency and material cost must be considered for practical and economic applications.

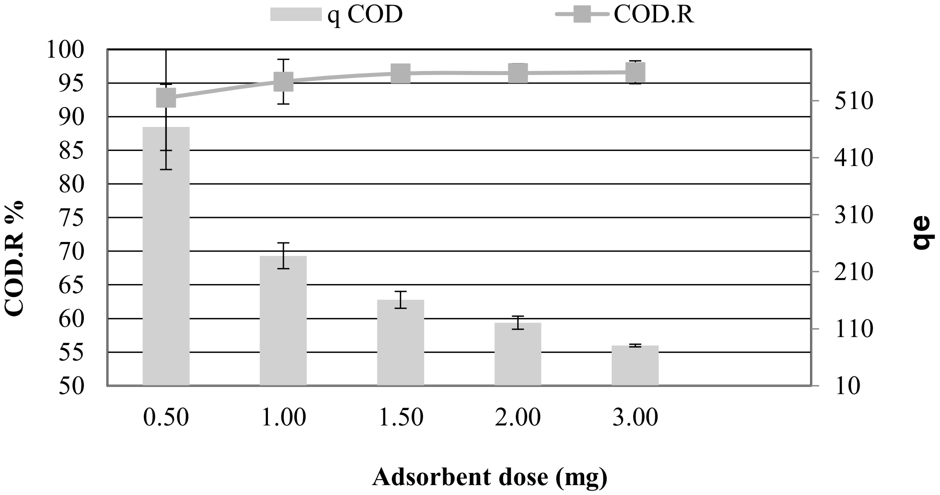

Fig. 6. Effect of adsorbent dose on COD removal efficiency and the adsorption capacity of COD at pH = 6, contact time=45 min, and agitation speed=200 rpm at 30^0c

3.2.4. Effect of contact time

Contact time is a vital parameter in adsorption processes, as it governs the interaction duration between the adsorbate and the adsorbent. To assess its influence, batch experiments were carried out at varying contact times ranging from 20 to 60 minutes, while keeping other parameters constant (adsorbent dose, pH, and temperature).

As shown in **Fig. 7**, the adsorption capacity increased with contact time, reaching a maximum of 484 mg/g at 45 minutes, along with a COD reduction of 96.8%. Initially, a rapid adsorption phase was observed, with the capacity rising from 430 mg/g at 20 minutes (86% COD reduction) to 464 mg/g at 30 minutes (92.8%), due to the availability of abundant active sites on the Orange Peel-derived activated carbon (OPAC). As time progressed, the rate of adsorption slowed, and equilibrium was nearly achieved at 45 minutes. Interestingly, a slight decline in adsorption capacity was recorded at 60 minutes (390 mg/g and 78% COD reduction), which may be attributed to possible desorption or redistribution of adsorbed molecules. This behavior suggests that 45 minutes is the optimal contact time for achieving maximum adsorption efficiency under the experimental conditions.

These findings confirm the typical adsorption profile, characterized by a fast initial uptake followed by a plateau, indicating equilibrium. Therefore, selecting an appropriate contact time is essential to optimize treatment performance and operational efficiency.

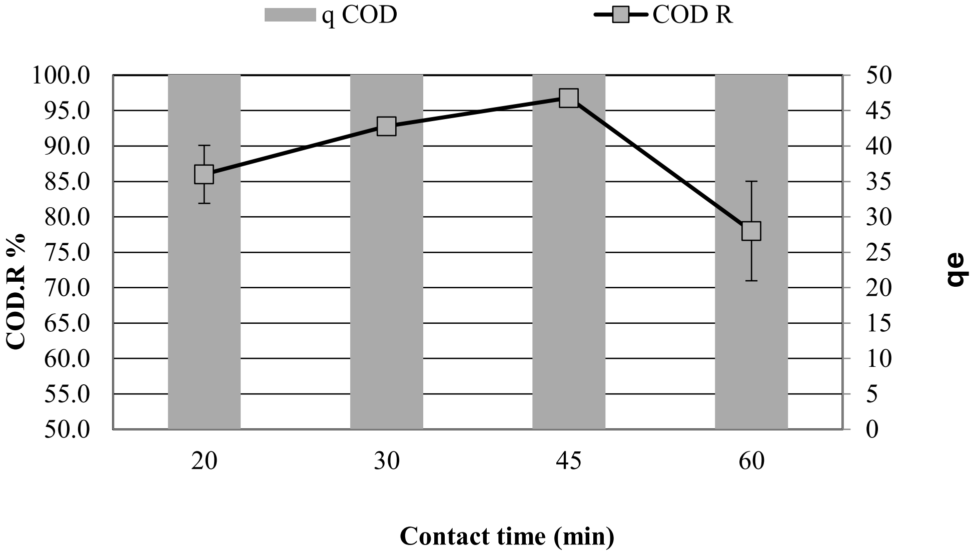

Fig. 7. **Effect** of contact time on COD on the removal efficiency and the adsorption capacity of COD at adsorbent dose =0.5 g, pH = 6, and agitation speed= 200 rpm at 30 ^{0}C.

3.2.5. Effect of stirring speed (rpm)

Stirring speed significantly affects the mass transfer rate of solutes from the bulk solution to the surface of the adsorbent, thereby influencing adsorption efficiency. In this study, batch adsorption experiments were performed at stirring speeds ranging from 200 to 700 rpm, while maintaining constant conditions for adsorbent dose, contact time, pH, and contaminant concentration.

As shown in **Fig. 8**, the adsorption capacity and COD reduction initially increased with stirring speed, reaching a maximum value of 484 mg/g and 96.8% COD reduction at 200 rpm. This enhancement is attributed to improved mixing and increased interaction between the Orange Peel-derived activated carbon (OPAC) and the contaminants in the solution. However, a gradual decline in adsorption performance was observed at higher stirring speeds. At 300 rpm, the capacity decreased to 426 mg/g with 85.2% COD reduction, and further declined at 500 rpm (390 mg/g, 78%) and 700 rpm (384 mg/g, 76.8%). This reduction can be linked to excessive turbulence at high speeds, which may cause desorption or reduce the effective contact time between adsorbate and adsorbent particles.

These findings indicate that 200 rpm is the optimal stirring speed under the tested conditions, as it ensures efficient mass transfer without introducing disruptive turbulence. Selecting an appropriate stirring speed is therefore crucial to maximizing adsorption efficiency in practical applications.

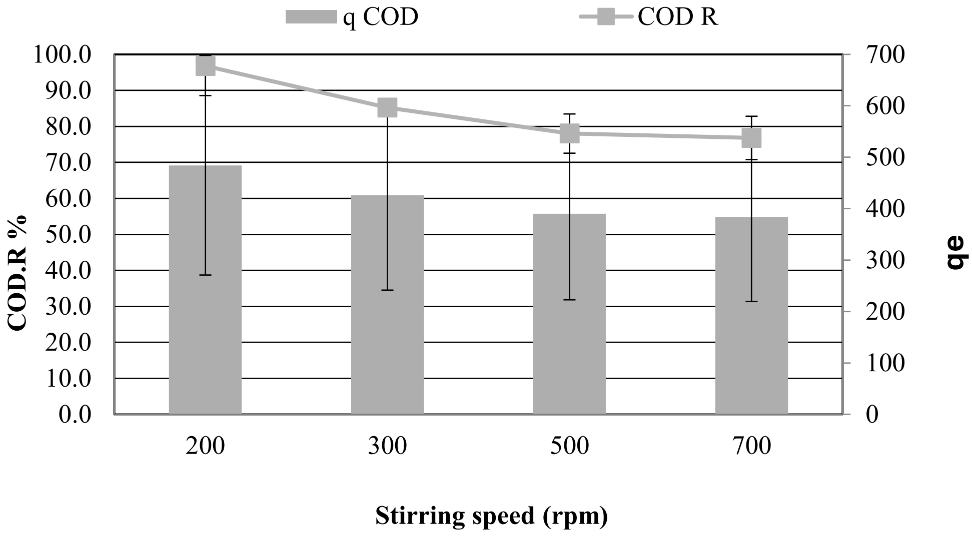

Fig. 8. **Effect** of stirring speed on COD removal efficiency and the adsorption capacity of COD at adsorbent dose =0.5 g, pH = 6, contact time=45 min and at 30 ^{0}C.

3.3. Optimal Conditions for Batch Adsorption

Based on the comprehensive evaluation of various operational parameters, the optimal conditions for maximizing the adsorption of organic contaminants from juice industry wastewater using Orange Peel-derived activated carbon (OPAC) were determined.

The highest adsorption capacity (464 mg/g) and COD reduction (92.8%) were observed at a pH of 6, indicating that a slightly acidic medium enhances the electrostatic attraction and interaction between the adsorbent and the contaminants. Regarding temperature, the optimum was 30°C, where the adsorption capacity remained at its maximum (464 mg/g), and COD removal reached 92.8%. Increasing temperature beyond this point resulted in a gradual decline in performance, suggesting that the adsorption process is exothermic under these conditions.

With respect to adsorbent dose, the best removal efficiency (96.6%) was achieved at 3 g/L, balancing between maximum contaminant removal and material economy. Although increasing the dose improved COD reduction, it caused a decrease in adsorption capacity per gram due to the fixed initial contaminant load.

For contact time, equilibrium was reached at 45 minutes, where the adsorption capacity peaked at 484 mg/g and COD reduction was 96.8%. Extending the contact time beyond this point did not significantly enhance removal, indicating the establishment of adsorption equilibrium.

Lastly, stirring speed had a notable effect, with the optimal performance obtained at 200 rpm, corresponding to an adsorption capacity of 484 mg/g and 96.8% COD reduction. Excessive agitation (≥500 rpm) caused a drop in performance, likely due to reduced contact efficiency and desorption effects caused by turbulent flow.

In conclusion, the optimal batch adsorption conditions for Orange peel-derived activated carbon (OPAC) were determined to be a pH of 6, a temperature of 30°C, an adsorbent dose of 3 g/L, a contact time of 45 minutes, and a stirring speed of 200 rpm. These parameters collectively ensure high adsorption efficiency and provide a solid foundation for scaling up the process for practical wastewater treatment applications.

3.4. Comparison with Commercial Activated Carbon

To evaluate the performance of Orange Peel-derived activated carbon (OPAC), its adsorption capacity and COD reduction efficiency were compared with those of a commercially available activated carbon (CAC) under identical operating conditions. The experiments were conducted using juice industry wastewater with a COD concentration of approximately 250 mg/L.

The results demonstrated that OPAC exhibited superior adsorption performance, achieving a maximum adsorption capacity of 484 mg/g and COD reduction of 96.8% under optimal conditions. In contrast, the commercial activated carbon showed a lower adsorption capacity of 370 mg/g and a COD reduction efficiency of 85% under the same parameters.

This difference in performance can be attributed to the higher surface area, better porosity, and the presence of functional groups in OPAC, as confirmed by characterization techniques such as BET, SEM, and FTIR. Additionally, the OPAC offered the advantage of being cost-effective and derived from agricultural waste, aligning with sustainable waste management and environmental protection practices.

In summary, the comparison clearly indicates that OPAC not only competes favorably with commercial activated carbon but may also offer enhanced performance for COD removal in industrial wastewater treatment, particularly in applications targeting low to moderate organic pollutant loads such as juice processing effluents.

4. Conclusions

The following conclusions can be drawn from the findings and discussions of the previous experiments:

- FTIR spectroscopy confirmed the presence of functional groups such as –OH, –COOH, C=O, and C=C, which enhance adsorption by promoting interactions with pollutant molecules.
- These functional groups indicate successful surface modification during carbonization and activation at 800 °C.
- XRD analysis revealed a broad peak at $2\theta \approx 25°$, indicating partial graphitization and the presence of layered carbon structures.
- Overall, the combined results from FTIR, XRD, and SEM analyses demonstrate that Orange Peel-derived activated carbon possesses the necessary surface chemistry, porosity, and structure to serve as an effective, low-cost, and sustainable adsorbent for environmental applications.
- Orange Peel-derived activated carbon (OPAC) was effectively used as a sustainable and efficient adsorbent for removing organic pollutants, especially chemical oxygen demand (COD), from juice industry wastewater.
- The optimal parameters were identified as pH 6, temperature 30°C, adsorbent dose 3 g/L, contact time 45 minutes, and stirring speed 200 rpm. Under these conditions, OPAC achieved a maximum adsorption capacity of 484 mg/g and COD removal efficiency of 96.8%, indicating high affinity for organic contaminants.
- OPAC outperformed commercial activated carbon (CAC) in both adsorption capacity and COD removal.
- The superior performance of OPAC was due to its enhanced surface area, high porosity, and rich surface functional groups, as confirmed by characterization studies.
- OPAC is a low-cost, renewable material derived from agricultural waste, promoting environmental sustainability and resource valorization.

5. References

[1] N. Akhtar, M. I. Syakir Ishak, S. A. Bhawani, and K. Umar, “Various natural and anthropogenic factors responsible for water quality degradation: A review,” *Water (Switzerland)*, vol. 13, no. 19, 2021, doi: 10.3390/w13192660.

[2] Q. Ali *et al.*, “Nanoremediation for heavy metal contamination: A review,” *Hybrid Adv.*, vol. 4, no. July, p. 100091, 2023, doi: 10.1016/j.hybadv.2023.100091.

[3] A. M. Gomaa *et al.*, “Trends and Future

Directions on Machine Learning for Enhancing Optimal Methods of Heavy Metal Ion Removal from Industrial Wastewater," vol. 1, no. 1, pp. 41–63, 2025.

[4] A. El Shahawy, A. M. M. El, S. E. L. Shatoury, and K. A. A. El Rahem, "Eco - friendly sustainable biofilters media for UASB effluent post - treatment in agrofood industry wastewater using design of experiments and LCA," *Int. J. Environ. Sci. Technol.*, no. 0123456789, 2025, doi: 10.1007/s13762-025-06582-3.

[5] V. A. Online, A. El Shahawy, M. F. Mubarak, and H. M. Abdulla, "AgNPs / GO / chitosan nanocomposite material †," pp. 29385–29398, 2022, doi: 10.1039/d2ra04693h.

[6] V. A. Online, A. El Shahawy, M. F. Mubarak, and H. M. Abdulla, "RSC Advances wastewater treatment †," pp. 17065–17084, 2022, doi: 10.1039/d2ra01612e.

[7] H. Sable, V. Kumar, V. Singh, S. Rustagi, S. Chahal, and V. Chaudhary, "Strategically engineering advanced nanomaterials for heavy-metal remediation from wastewater," *Coord. Chem. Rev.*, vol. 518, no. May, p. 216079, 2024, doi: 10.1016/j.ccr.2024.216079.

[8] T. Ahmed *et al.*, "Current trends and future prospective in nanoremediation of heavy metals contaminated soils: A way forward towards sustainable agriculture," *Ecotoxicol. Environ. Saf.*, vol. 227, p. 112888, 2021, doi: 10.1016/j.ecoenv.2021.112888.

[9] T. E. Oladimeji, M. Oyedemi, M. E. Emetere, O. Agboola, and J. B. Adeoye, "Heliyon Review on the impact of heavy metals from industrial wastewater effluent and removal technologies," *Heliyon*, vol. 10, no. 23, p. e40370, 2024, doi: 10.1016/j.heliyon.2024.e40370.

[10] S. Kato and Y. Kansha, *Comprehensive review of industrial wastewater treatment techniques*, vol. 31, no. 39. Springer Berlin Heidelberg, 2024.

[11] E. F. Strategies *et al.*, "Comparing Conventional and Advanced Approaches for Heavy Metal Removal in Wastewater Treatment : An In-Depth Review," 2024.

[12] M. Ammar, E. Yousef, S. Ashraf, and J. Baltrusaitis, "Removal of Inorganic Pollutants and Recovery of Nutrients from Wastewater Using Electrocoagulation: A Review," *Separations*, vol. 11, no. 11, 2024, doi: 10.3390/separations11110320.

[13] E. Mutegoa, "Efficient techniques and practices for wastewater treatment : an update," *Discov. Water*, 2024, doi: 10.1007/s43832-024-00131-8.

[14] M. Chen, R. Xu, Y. Wu, J. Xiong, S. Z. Keleş, and N. P. Hankins, "Application of polyelectrolytes for contaminant removal and recovery during water and wastewater treatment: A critical review," *J. Water Process Eng.*, vol. 64, no. June, 2024, doi: 10.1016/j.jwpe.2024.105528.

[15] B. S. Rathi and P. S. Kumar, "Application of adsorption process for effective removal of emerging contaminants from water and wastewater," *Environ. Pollut.*, vol. 280, p. 116995, 2021, doi: 10.1016/j.envpol.2021.116995.

[16] S. Kathi and A. El Din Mahmoud, "Trends in effective removal of emerging contaminants from wastewater: A comprehensive review," *Desalin. Water Treat.*, vol. 317, no. January, p. 100258, 2024, doi: 10.1016/j.dwt.2024.100258.

[17] M. S. Akhtar, S. Ali, and W. Zaman, "Innovative Adsorbents for Pollutant Removal: Exploring the Latest Research and Applications," *Molecules*, vol. 29, no. 18, pp. 1–37, 2024, doi: 10.3390/molecules29184317.

[18] A. El-Baz, I. Hendy, A. Dohdoh, and M. Srour, "Adsorption technique for pollutants removal; current new trends and future challenges – A Review," *Egypt. Int. J. Eng. Sci. Technol.*, vol. 32, no. 1, pp. 1–24, 2020, doi:

10.21608/eijest.2020.45536.1015.

[19] N. Muttil, S. Jagadeesan, A. Chanda, M. Duke, and S. K. Singh, “Production, Types, and Applications of Activated Carbon Derived from Waste Tyres: An Overview,” *Appl. Sci.*, vol. 13, no. 1, 2023, doi: 10.3390/app13010257.

[20] E. H. Sujiono *et al.*, “Fabrication and characterization of coconut shell activated carbon using variation chemical activation for wastewater treatment application,” *Results Chem.*, vol. 4, no. February, p. 100291, 2022, doi: 10.1016/j.rechem.2022.100291.

[21] M. M. Alam *et al.*, “The potentiality of rice husk-derived activated carbon: From synthesis to application,” *Processes*, vol. 8, no. 2, 2020, doi: 10.3390/pr8020203.

[22] K. Kuśmierek, A. Świątkowski, T. Kotkowski, R. Cherbański, and E. Molga, “Adsorption on activated carbons from end-of-life tyre pyrolysis for environmental applications. Part II. Adsorption from aqueous phase,” *J. Anal. Appl. Pyrolysis*, vol. 158, no. July, 2021, doi: 10.1016/j.jaap.2021.105206.

[23] N. H. Dana, M. Borghei, A. Takdastan, A. H. Javid, and M. A. Zazouli, “Magnetic carbon nanocomposite derived from waste tire rubber for atrazine removal from aqueous solutions,” *Desalin. Water Treat.*, vol. 252, pp. 219–232, 2022, doi: 10.5004/dwt.2022.28141.

[24] H. Daraei and A. Mittal, “Investigation of adsorption performance of activated carbon prepared from waste tire for the removal of methylene blue dye from wastewater,” *Desalin. Water Treat.*, vol. 90, pp. 294–298, 2017, doi: 10.5004/dwt.2017.21344.

[25] R. Aziam *et al.*, “Kinetics, isothermal and thermodynamic studies of the adsorption of Acid Blue 113 dye from aqueous solution onto dried tea waste as natural adsorbent,” *Desalin. Water Treat.*, vol. 315, pp. 387–398, 2023, doi: 10.5004/dwt.2023.30153.

[26] B. Alvez-Tovar, P. S. Scalize, G. Angiolillo-Rodríguez, A. Albuquerque, M. N. Ebang, and T. F. de Oliveira, “Agro-Industrial Waste Upcycling into Activated Carbons: A Sustainable Approach for Dye Removal and Wastewater Treatment,” *Sustain.*, vol. 17, no. 5, pp. 1–25, 2025, doi: 10.3390/su17052036.

[27] G. Enaime, S. Dababat, M. Wichern, and M. Lübken, “Olive mill wastes: from wastes to resources,” *Environ. Sci. Pollut. Res.*, vol. 31, no. 14, pp. 20853–20880, 2024, doi: 10.1007/s11356-024-32468-x.

[28] N. Jagadeesh and B. Sundaram, “Adsorption of Pollutants from Wastewater by Biochar: A Review,” *J. Hazard. Mater. Adv.*, vol. 9, no. May 2022, 2023, doi: 10.1016/j.hazadv.2022.100226.

[29] K. S. Bharathi and S. T. Ramesh, “Removal of dyes using agricultural waste as low-cost adsorbents: a review,” *Appl. Water Sci.*, vol. 3, no. 4, pp. 773–790, 2013, doi: 10.1007/s13201-013-0117-y.

[30] D. Sarkar, T. F. Panicker, R. Kumar Mishra, and M. Srinivas Kini, “A comprehensive review of production and characterization of biochar for removal of organic pollutants from water and wastewater,” *Water-Energy Nexus*, vol. 7, pp. 243–265, 2024, doi: 10.1016/j.wen.2024.11.001.

[31] Y. Trivedi *et al.*, “Biochar potential for pollutant removal during wastewater treatment: A comprehensive review of separation mechanisms, technological integration, and process analysis,” *Desalination*, vol. 600, no. August 2024, p. 118509, 2025, doi: 10.1016/j.desal.2024.118509.

[32] R. Zhao, “A review on the catalytic ozonation of pollutants in wastewater by heteroelements-doped biochar: Internal and external doping strategies,” *Alexandria Eng. J.*, vol. 119, no. January, pp. 35–44, 2025, doi: 10.1016/j.aej.2025.01.088.

[33] M. A. Ashraf, K. S. Balkhair, A. J. Khan Chowdhury, and M. M. Hanafiah, “Treatment of taman beringin landfill leachate using the columntechnique,”

Desalin. Water Treat., vol. 149, no. 2019, pp. 370–387, 2019, doi: 10.5004/dwt.2019.23839.

[34] T. N. Dharmapriya, H. Y. Shih, and P. J. Huang, “Facile Synthesis of Hydrogel-Based Ion-Exchange Resins for Nitrite/Nitrate Removal and Studies of Adsorption Behavior,” *Polymers (Basel).*, vol. 14, no. 7, 2022, doi: 10.3390/polym14071442.

[35] K. Jedynak, B. Szczepanik, N. Rędzia, P. Slomkiewicz, A. Kolbus, and P. Rogala, “Ordered mesoporous carbons for adsorption of paracetamol and non-steroidal anti-inflammatory drugs: Ibuprofen and naproxen from aqueous solutions,” *Water (Switzerland)*, vol. 11, no. 5, pp. 1–21, 2019, doi: 10.3390/w11051099.

[36] S. E. Abd Elhafez, A. El-Maghraby, and N. A. Taha, “Adsorption studies of cationic dye on raw and modified sugarcane bagasse from aqueous solutions: Kinetic and isotherm aspects,” *Egypt. J. Chem.*, vol. 64, no. 3, pp. 1593–1600, 2021, doi: 10.21608/EJCHEM.2020.41762.2846.

[37] M. Bounaas, A. Bouguettoucha, D. Chebli, K. Derbal, A. Benalia, and A. Pizzi, “Effect of Washing Temperature on Adsorption of Cationic Dyes by Raw Lignocellulosic Biomass,” *Appl. Sci.*, vol. 14, no. 22, 2024, doi: 10.3390/app142210365.

[38] T. C. Maponya, K. Makgopa, T. R. Somo, and K. D. Modibane, “Highlighting the Importance of Characterization Techniques Employed in Adsorption Using Metal–Organic Frameworks for Water Treatment,” *Polymers (Basel).*, vol. 14, no. 17, 2022, doi: 10.3390/polym14173613.

[39] H. Ouachtak *et al.*, “Combined molecular dynamics simulations and experimental studies of the removal of cationic dyes on the eco-friendly adsorbent of activated carbon decorated montmorillonite Mt@AC,” *RSC Adv.*, vol. 13, no. 8, pp. 5027–5044, 2023, doi: 10.1039/d2ra08059a.

[40] M. Gojeh *et al.*, “Characterization and Adsorptive Capacity of Gutta Percha Leaf,” vol. 1, no. October, pp. 1–9, 2024.

[41] C. A. Guerrero-Fajardo, L. Giraldo, and J. C. Moreno-Pirajan, “Isotherm, thermodynamic, and kinetic studies of dye adsorption on graphene oxides with varying oxidation degrees,” *Results Eng.*, vol. 26, no. January, p. 104558, 2025, doi: 10.1016/j.rineng.2025.104558.

[42] Z. Tigrine *et al.*, “Sustainable Activated Carbon from Agricultural Waste: A Study on Adsorption Efficiency for Humic Acid and Methyl Orange Dyes,” *Sustain.*, vol. 16, no. 21, 2024, doi: 10.3390/su16219308.

[43] H. Khan *et al.*, “From pollutant to purifier: Leveraging plastic waste-derived activated carbon for sustainable water remediation solutions,” *J. Environ. Manage.*, vol. 375, no. August 2024, p. 124202, 2025, doi: 10.1016/j.jenvman.2025.124202.

[44] G. A. El, A. M. Gomaa, and M. Daowd, “Circular Economy in Engineering Education : Enhancing Quality through Project-Based Learning and Assessment,” vol. 1, pp. 1–17, 2024.