Case Studies in Chemical and Environmental Engineering 10 (2024) 100791

Contents lists available at ScienceDirect

Case Studies in Chemical and Environmental Engineering

journal homepage: www.sciencedirect.com/journal/case-studies-in-chemical-and-environmental-engineering

Case Report

Utilization of banana peel-derived activated carbon for the removal of heavy metals from industrial wastewater

Timoth Mkilima [a,*], Yerkebulan Zharkenov [b,**], Aisulu Abduova [c], Nursulu Sarypbekova [d], Nurlan Kudaibergenov [b], Kuandyk Sakanov [e], Gyulnara Zhukenova [e], Zhumabek Omarov [f], Parida Sultanbekova [g], Gulmira Kenzhaliyeva [c]

[a] *Department of Environmental Engineering and Management, The University of Dodoma, P. O. Box 259, Dodoma, Tanzania*
[b] *Department of Civil Engineering, Faculty of Architecture and Construction, L.N. Gumilyov Eurasian National University, 010000, Astana, Kazakhstan*
[c] *Department of Ecology, The higher school of chemical engineering and biotechnology, M. Auezov South Kazakhstan University, 160012, Shymkent, Kazakhstan*
[d] *Department of chemistry and pharmaceutical engineering, The higher school of chemical engineering and biotechnology, M. Auezov South Kazakhstan University, 160012, Shymkent, Kazakhstan*
[e] *Department of Industrial, Civil and Transport Construction, Faculty of Architecture and Construction, Toraighyrov University, 140008, Pavlodar, Kazakhstan*
[f] *Department of Architecture and Design, Faculty of Architecture and Construction, Toraighyrov University, 140008, Pavlodar, Kazakhstan*
[g] *Department of Water Resources, Land Use and Agricultural Technology, M. Auezov South Kazakhstan University, Shymkent, 160012, Shymkent, Kazakhstan*

ARTICLE INFO

Keywords:
Wastewater treatment
Sustainable adsorbents
Water quality
Cadmium
Lead

ABSTRACT

Metal plating industries generate wastewater containing heavy metals, necessitating effective treatment methods to mitigate environmental contamination. This study investigated the potential of banana peel-derived activated carbon (BPAC) and commercial activated carbon for heavy metal removal, addressing a pressing environmental concern. The analysis encompassed diverse pH levels, crucial for real-world applicability, offering valuable insights into adsorption capacities and kinetics. The results revealed competitive performance of both materials, with typical lead (Pb) removal ranging from 4 to 6 mg/g and cadmium (Cd) from 3 to 5 mg/g. Commercial activated carbon exhibited slightly superior adsorption kinetics and capacities, highlighting its efficacy in heavy metal removal. Throughout the study, optimizing dosage proved essential for maximizing removal efficiency, emphasizing the practical implications of this research. Furthermore, the time-dependent behavior of adsorption kinetics underscored the importance of extended contact times for enhanced removal. Generally, BPAC emerged as a promising solution for heavy metal removal from industrial wastewater. It consistently achieved removal efficiencies typically ranging from 75 % to more than 90 %, making it a viable alternative in the realm of wastewater treatment. At pH 4, BPAC demonstrated significantly higher adsorption capacity, with lead (Pb) at 5.50 ± 0.20 (mg/g) and cadmium (Cd) at 4.10 ± 0.15 (mg/g), compared to slightly lower values for commercial activated carbon, Pb at 5.20 ± 0.25 (mg/g) and Cd at 3.90 ± 0.20 (mg/g). This study contributes significantly to wastewater treatment methodologies, offering sustainable and efficient approaches to address heavy metal contamination in industrial effluents.

1. Introduction

The escalating global industrialization has led to a proportional increase in the generation of wastewater, particularly from industrial processes, containing a myriad of contaminants, including heavy metals. Heavy metal contamination poses severe environmental and health risks, necessitating efficient wastewater treatment strategies [1]. Consequently, there exists an urgent necessity for the implementation of effective wastewater treatment methods to counteract these risks and ensure the protection of both ecosystems and human well-being. In light of this imperative, the investigation of natural adsorbents as a viable solution has garnered increasing attention in recent years [2]. These natural adsorbents offer promising prospects due to their abundance, cost-effectiveness, and potential for selective removal of heavy metals, thus presenting an attractive avenue for addressing the challenges posed by industrial wastewater contamination [3].

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[*] Corresponding author.
[**] Corresponding author.
E-mail addresses: tmkilima@gmail.com (T. Mkilima), berdenovich@gmail.com (Y. Zharkenov).

https://doi.org/10.1016/j.cscee.2024.100791
Received 10 May 2024; Received in revised form 4 June 2024; Accepted 8 June 2024

Conventional wastewater treatment methods, including coagulation-flocculation [4], sedimentation [5], and chemical precipitation [6], have historically served as the primary means of addressing industrial wastewater contamination. Despite their widespread use, these methods are not without drawbacks. High operational costs, stemming from the need for specialized equipment and chemical reagents, pose a significant financial burden for industrial facilities. Additionally, these methods often result in the generation of large volumes of sludge, which require further treatment and disposal, increasing operational complexity and costs further. Furthermore, conventional methods may exhibit limited efficacy in removing certain contaminants, particularly heavy metals, which can persist in effluent streams at concentrations that exceed regulatory limits [7]. In contrast, natural adsorbents present a compelling alternative for wastewater treatment due to their unique properties and advantages [8]. These materials, derived from renewable sources such as agricultural waste or natural minerals [9], are readily available and often incur minimal production costs. Their biodegradability offers environmental benefits, reducing the accumulation of non-biodegradable waste associated with conventional treatment methods [10]. Moreover, natural adsorbents demonstrate a remarkable capacity for selective adsorption of contaminants, including heavy metals, from wastewater streams. This selectivity allows for targeted removal of specific contaminants, enhancing treatment efficiency while minimizing the consumption of resources [11]. The utilization of natural adsorbents in wastewater treatment represents a paradigm shift towards sustainable and cost-effective contamination mitigation strategies [12]. By harnessing the abundant resources provided by nature, industrial facilities can reduce their environmental footprint and operational costs while achieving regulatory compliance and safeguarding public health. Moreover, the versatility of natural adsorbents allows for customization and optimization of treatment processes to suit specific wastewater compositions and treatment objectives [13]. As such, the integration of natural adsorbents into existing wastewater treatment infrastructure holds immense promise for addressing the challenges posed by industrial wastewater contamination in a holistic and environmentally conscious manner [14].

Numerous studies have explored the potential of natural adsorbents for heavy metal removal from wastewater. However, the majority of these studies have focused on adsorbents derived from sources such as activated carbon from coal or biomass. For instance, Li et al. [15], utilized magnetic cyclodextrin chitosan-functionalized graphene oxide for chromium removal, leveraging the advantageous properties of magnetic cyclodextrin chitosan, such as its high adsorption capacity and magnetic characteristics facilitating separation processes. Lo et al. [16], investigated activated carbon derived from moso and ma bamboo, achieving complete chromium removal with once-activated ma bamboo and 91.7 % removal with twice-activated ma bamboo. Luo et al. [17], synthesized nanocomposites comprising manganese dioxide/iron oxide/acid-oxidized multi-walled carbon nanotubes for chromium removal. Cronje et al. [18], demonstrated chromium removal by activating sugarcane bagasse with zinc chloride, achieving over 87 % chromium removal at an optimal pH of 8.58. Shen et al. [19], employed coconut coir-derived char for chromium removal, reporting a maximum removal efficiency of 70 %. Lugo-Lugo et al. [20] biosorbed chromium onto the pre-treated orange peel, evaluating both single-phase (chromium only) and binary-phase (chromium with iron) systems. In single-phase conditions, chromium removal percentage and adsorption capacity were 51 % and 4.79 mg/g, respectively, while in binary-phase conditions, they were 79 % and 7.60 mg/g, respectively. Despite the growing interest in natural adsorbents, there remains a notable gap in the literature concerning the utilization of banana peel-derived activated carbon (BPAC) specifically for heavy metal removal from industrial wastewater. This study seeks to address this gap by investigating the efficacy of BPAC as a novel adsorbent in this context. The underlying mechanisms governing the adsorption behavior of BPAC towards heavy metals have yet to be fully elucidated. This study aims to contribute to the understanding of these mechanisms through comprehensive kinetic and isotherm studies. By systematically investigating key adsorption parameters such as pH and dosage, the study seeks to provide insights into the adsorption mechanism and equilibrium behavior of BPAC. Despite extensive endeavors within the realm of wastewater treatment to investigate numerous adsorbents, a noticeable gap persists in understanding the prospective utilization of BPAC for the removal of heavy metals. Although investigations have scrutinized a wide array of natural adsorbents, the precise efficacy of BPAC in addressing this pivotal aspect remains substantially underexplored.

This study investigates the potential of BPAC for the removal of lead (Pb) and cadmium (Cd) from industrial wastewater. Through batch adsorption experiments and comparative analysis with commercial activated carbon, the study evaluates the adsorption efficiency of BPAC and explore the influence of key parameters such as pH and dosage. The findings of this study have significant implications for the development of sustainable and cost-effective wastewater treatment technologies, addressing the pressing environmental concerns associated with heavy metal contamination.

2. Materials and methods

2.1. Sample collection

The study retrieved a total of 24 wastewater samples from the effluent discharge point of a metal plating facility. Sampling was conducted over the course of one year to ensure a comprehensive representation of the wastewater characteristics. The sampling protocols were meticulously designed and followed. Samples were collected directly from the effluent discharge point, ensuring they represented the contaminants typically associated with metal processing activities. The sampling was conducted quarterly, with six samples collected each season. This approach ensured that potential seasonal variations in contaminant levels were captured. Each sample was immediately stored in pre-cleaned, acid-washed polyethylene bottles to prevent contamination and transported to the laboratory under cooled conditions (4 °C). All samples were analyzed within 24 hours of collection to maintain their integrity. The analytical procedures included a thorough characterization of each sample. pH was measured using a calibrated pH meter, and conductivity was determined with a conductivity meter (METTLER TOLEDO, Columbus, OH 43240 USA). Total Suspended Solids (TSS) concentrations were measured by filtering a known volume of the sample through a pre-weighed filter paper, followed by drying and weighing the residue. Heavy metals, specifically lead (Pb) and cadmium (Cd), were quantified using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (PerkinElmer, Winter Street, USA) for high accuracy and sensitivity. Seasonal variation was an important aspect of this study. By collecting samples quarterly over one year, the study accounted for any potential changes in the effluent's characteristics due to seasonal variations in industrial activities, weather patterns, or other factors. Twelve samples were collected in each season: wet and dry. This distribution allowed for a detailed analysis of how the contaminant levels might fluctuate throughout the year, ensuring that the study's findings were robust and representative of year-round conditions.

2.2. Baseline data

Wastewater samples were collected from the effluent discharge point of a metal plating facility, ensuring the representation of contaminants typically associated with metal processing activities (Table 1). A total of 24 samples were retrieved a year, capturing seasonal variations. Samples were stored in pre-cleaned, acid-washed polyethylene bottles, transported under cooled conditions, and analyzed within 24 hours. The characterization included pH measurement using a calibrated pH meter, conductivity using a conductivity meter, TSS determination by filtering and weighing residues, and quantification of lead (Pb) and cadmium

Table 1
Raw wastewater analysis.

Parameter	Value ± SD
pH	4.0 ± 0.2
Conductivity (μS/cm)	1812 ± 151
TSS (mg/L)	341 ± 28
Pb (mg/L)	1.3 ± 0.05
Cd (mg/L)	1.2 ± 0.03

(Cd) using ICP-MS or AAS. The comprehensive analysis provided vital baseline data necessary for assessing the adsorption capacity of the chosen natural adsorbent and evaluating the overall efficacy of the wastewater treatment process. The raw wastewater exhibited a pH of 4.0 ± 0.2, conductivity of 1812 ± 150 μS/cm, TSS concentration of 341 ± 28 mg/L, lead concentration of 1.3 ± 0.05 mg/L, and cadmium concentration of 0.2 ± 0.03 mg/L.

2.3. Banana peel-derived activated carbon

BPAC was prepared through a series of controlled steps to ensure optimal adsorption properties. Initially, banana peels sourced from local markets were washed, dried, and ground into fine particles to enhance surface area and facilitate uniform pyrolysis. The ground peels were then subjected to pyrolysis in a tube furnace under an inert atmosphere at a temperature of 600 °C for 2 hours. This thermal treatment led to the carbonization of the organic components of the banana peels, resulting in the formation of a carbon-rich material. Following carbonization, the resulting carbonized banana peel material underwent activation to enhance its porosity and surface area. Steam activation was employed, wherein the carbonized material was exposed to steam at a temperature of 800 °C for 1 hour. This process created a network of micropores and mesopores within the carbon structure, maximizing its adsorption capacity. The activated carbon was then washed with distilled water to remove any residual impurities and dried at 110 °C for 24 hours. The BPAC was characterized for its physicochemical properties using advanced analytical techniques. Surface area and pore size distribution were determined using nitrogen adsorption-desorption isotherms obtained via Brunauer-Emmett-Teller (BET) analysis. The surface area of BPAC was found to be 800 m^2/g, with a predominantly microporous structure characterized by pore sizes ranging from 1 to 2 nm. The characterized BPAC demonstrated excellent adsorption properties, owing to its high surface area and optimized pore structure. The abundant presence of micropores provided ample active sites for the adsorption of heavy metal ions from wastewater. Additionally, the utilization of banana peel waste as a precursor for activated carbon production offered environmental benefits by repurposing agricultural by-products and reducing waste generation.

2.4. Experimental procedure

2.4.1. Batch adsorption experiments

BPAC and commercial activated carbon were prepared in dosages ranging from 1 to 10 g/L. Each dosage was accurately weighed using an analytical balance. BPAC was synthesized through controlled pyrolysis and activation of banana peels, while commercial activated carbon was obtained from a reputable supplier. Specifically, 100 mL of industrial wastewater was accurately dispensed into individual glass beakers using a graduated cylinder to maintain consistency. To each beaker, precise dosages of adsorbents, ranging from 1 to 10 g/L, were added using a laboratory spatula. Subsequently, the contents of each beaker underwent vigorous stirring using a magnetic stirrer set at 200 rpm for 15 minutes (Fig. 1). This extended stirring duration ensured thorough mixing and homogenous dispersion of the adsorbent particles within the wastewater matrix, facilitating optimal contact between the adsorbents and the heavy metal ions present in the wastewater for efficient adsorption. The pH of each solution was adjusted to the desired range using pH buffers. Initially, the initial pH of the industrial wastewater was measured using a calibrated pH meter (Infitek, Shandong, China). Subsequently, pH adjustments were made by carefully adding drops of either 0.1 M HCl or 0.1 M NaOH solutions to achieve the desired pH range of 5.0–9.0. The pH meter was recalibrated before each adjustment

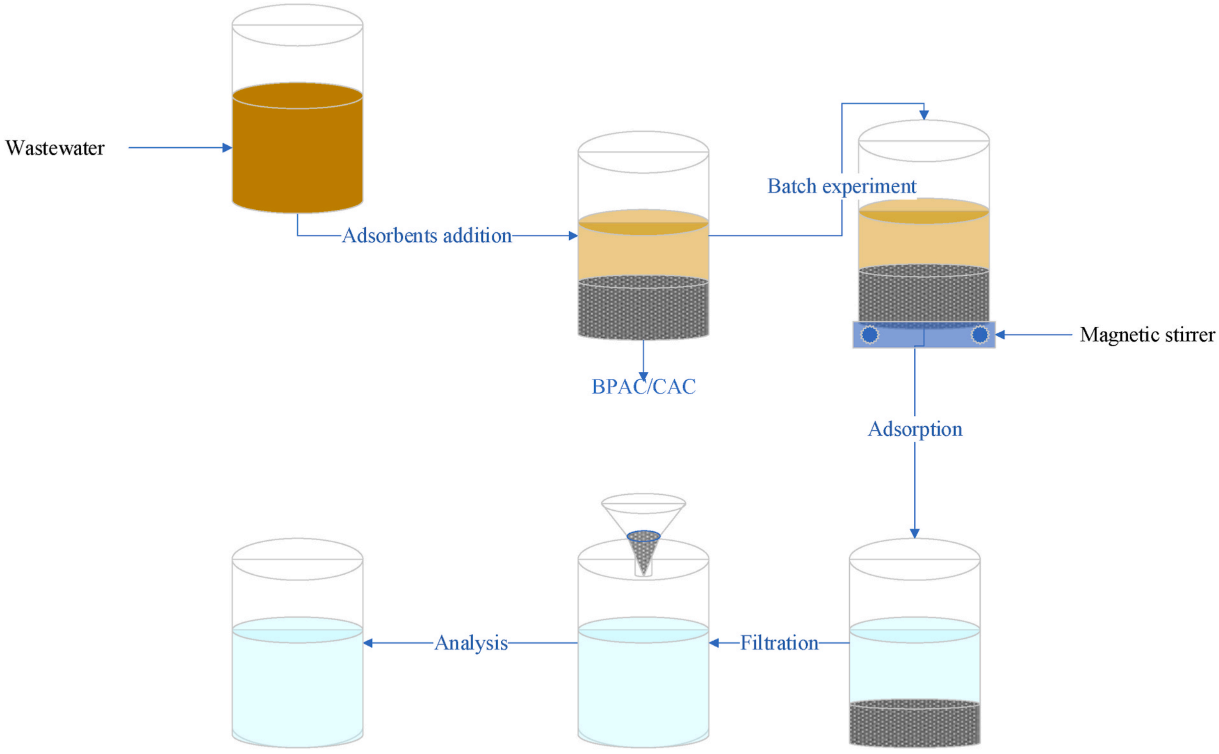


Fig. 1. Schematic diagram of the batch adsorption experiment.

to maintain accuracy and consistency across all experimental setups. pH adjustments were crucial as they influenced the surface charge of the adsorbents and the speciation of heavy metal ions, thereby directly impacting the adsorption process. Mixtures underwent continuous stirring at 200 rpm for 2 hours using a magnetic stirrer. This facilitated interaction between adsorbents and heavy metal ions, with stirring ensuring uniform distribution and enhanced mass transfer kinetics. After 2 hours, samples were centrifuged at 3000 rpm for 10 minutes to separate the adsorbent material. This allowed for easy recovery of the supernatant for subsequent analysis, minimizing sedimentation of adsorbent particles. The supernatant was transferred to cuvettes for analysis of residual lead (Pb) and cadmium (Cd) concentrations using a UV–visible spectrophotometer. Calibration curves from standard solutions enabled accurate quantification, assessing the adsorption efficiency of the adsorbents.

2.4.2. *Effect of pH and time*

This study rigorously investigated the influence of pH, dosage, and time on the adsorption efficiency of BPAC and commercial activated carbon for heavy metal removal from wastewater. Batch adsorption experiments were conducted at varying pH levels ranging from acidic to alkaline conditions. Dosages of adsorbents were systematically varied across different concentrations to assess their impact on adsorption capacity. Additionally, the adsorption kinetics over time were analyzed, with experiments conducted at multiple time intervals to elucidate temporal trends in the adsorption process. For pH, the investigation covered a range from acidic (pH 4.0) to slightly alkaline (pH 9.0), reflecting the diverse pH levels commonly found in wastewater streams from various industrial processes. Dosages of adsorbents were explored at concentrations of 1 g/L, 5 g/L, and 10 g/L, encompassing a spectrum of dosing scenarios relevant to practical applications. Time intervals ranging from 30 minutes to 120 minutes were examined to capture the dynamic adsorption kinetics over different durations, mirroring the timeframes typically involved in batch adsorption processes. These typical values were carefully selected to ensure a comprehensive assessment of the effects of pH, dosage, and time on the adsorption performance of the investigated adsorbents.

2.5. *Adsorption kinetics and isotherms*

2.5.1. *Kinetic studies*

For the kinetic studies, the rate of lead (Pb) and cadmium (Cd) adsorption onto BPAC was investigated. The experiments were conducted by monitoring the changes in metal ion concentrations over time. The pseudo-first-order and pseudo-second-order kinetic models were employed to analyze the adsorption kinetics. The pseudo-first-order kinetic model is expressed in Equation (1) [21].

$$\log(q_e - q_t) = \log(q_e) - \frac{k_1}{2.303} \times t \tag{1}$$

Whereby, q_t is the amount of metal ions adsorbed at time t (mg/g), q_e is the amount of metal ions adsorbed at equilibrium (mg/g), k_1 is the rate constant of the pseudo-first-order model (1/min), and t is the contact time (min). The pseudo-second-order kinetic model is given by Equation (2) [22].

$$\frac{t}{q_t} = \frac{1}{k_2 \times q_e^2} + \frac{t}{q_e} \tag{2}$$

Whereby, k_2 is the rate constant of the pseudo-second-order model (g/(mg·min)).

2.5.2. *Isotherm studies*

For the isotherm studies, adsorption isotherms were conducted to elucidate the equilibrium behavior of lead (Pb) and cadmium (Cd) adsorption onto BPAC. Two commonly used isotherm models, the Langmuir and Freundlich isotherm models, were employed to analyze the adsorption data and determine the adsorption capacity and affinity of BPAC for Pb and Cd ions. The Langmuir isotherm model is expressed in Equation (3) [23].

$$\frac{C_e}{q_e} = \frac{1}{q_m} \times \frac{1}{1 + \frac{C_e}{K_L}} \tag{3}$$

Whereby, q_e is the amount of metal ions adsorbed at equilibrium (mg/g), C_e is the equilibrium concentration of metal ions in solution (mg/L), q_m is the maximum adsorption capacity (mg/g), and K_L is the Langmuir adsorption equilibrium constant (L/mg), which is related to the energy of adsorption.

On the other hand the Freundlich isotherm is an empirical equation that describes the relationship between the concentration of a solute in a solution and the amount adsorbed onto an adsorbent surface. The Freundlich isotherm model is given by Equation (4) [24].

$$\log(q_e) = \log(K_F) + \frac{1}{n} \times \log(C_e) \tag{4}$$

Whereby, K_F is the Freundlich constant representing the adsorption capacity (mg/g) and n is the Freundlich exponent characterizing the adsorption intensity.

2.6. *Comparative analysis*

In a direct comparison, the adsorption efficacy of BPAC was compared with that of a commercially available activated carbon under identical experimental parameters. Using matched dosages of BPAC and commercial activated carbon, along with consistent initial concentrations of lead (Pb) and cadmium (Cd) in the industrial wastewater sample, ensured a precise comparison. Both adsorbents underwent identical pH adjustments, stirring speeds, and contact times to eliminate variables. Post-adsorption, concentrations of Pb and Cd in the supernatant were meticulously analyzed via UV–visible spectrophotometry to ascertain the efficiency of each adsorbent. Quantitative assessment of adsorption capacities, kinetics, and equilibrium behavior using appropriate models facilitated a rigorous comparative analysis. This meticulous approach offered specific insights into the relative performance of BPAC versus commercial activated carbon for heavy metal removal from industrial wastewater, crucial for informed decision-making in wastewater treatment applications.

2.7. *Data analysis*

In the data analysis phase, several key parameters were calculated to assess the adsorption performance of BPAC and commercial activated carbon and conduct a statistical comparison between them. Adsorption capacity, expressed as the amount of metal ions adsorbed per unit mass of adsorbent, was determined using the equilibrium adsorption data obtained from the experiments. Percentage removal of lead (Pb) and cadmium (Cd) was calculated based on the initial and equilibrium concentrations of the metal ions in the wastewater samples. Additionally, kinetic parameters such as the rate constants for pseudo-first-order and pseudo-second-order models were computed to characterize the adsorption kinetics of BPAC and commercial activated carbon. Similarly, isotherm parameters including the maximum adsorption capacity and equilibrium constant were determined using the Langmuir and Freundlich isotherm models. Statistical analysis, specifically as t-tests was then conducted to compare the performance of BPAC and commercial activated carbon in terms of adsorption capacity, percentage removal, and kinetic and isotherm parameters. These analyses provided valuable insights into the relative efficacy of the two adsorbents for heavy metal removal from industrial wastewater and helped in identifying any significant differences between them.

3. Results

3.1. BET analysis

The results of the BET analysis reveal notable differences in the porous characteristics between BPAC and commercial activated carbon (Table 2). While both materials exhibit substantial surface areas, with BPAC measuring 841 ± 20 m^2/g and commercial activated carbon measuring 953 ± 25 m^2/g, the latter demonstrates a slightly higher surface area. Similarly, the pore volume of commercial activated carbon (0.52 ± 0.03 cm^3/g) is slightly greater than that of BPAC (0.47 ± 0.02 cm^3/g), indicating a potentially higher adsorption capacity. Moreover, commercial activated carbon features a larger average pore diameter (2.5 ± 0.2 nm) compared to BPAC (2.1 ± 0.1 nm), suggesting differences in pore structure. However, BPAC exhibits a marginally higher total micropore volume (0.26 ± 0.028 cm^3/g) compared to commercial activated carbon (0.33 ± 0.031 cm^3/g), indicating a greater proportion of micropores available for adsorption. Overall, while commercial activated carbon demonstrates slightly superior porous characteristics, BPAC exhibits competitive properties, particularly in terms of micropore volume, which could influence its adsorption performance in wastewater treatment applications.

3.2. Removal efficiency without pH adjustment

The removal efficiency results indicate that both BPDAC and Commercial Activated Carbon (CAC) exhibit high efficiency in removing various contaminants from water (Fig. 2). BPAC demonstrates a conductivity removal efficiency of 79.5 %, slightly lower than that of Commercial Activated Carbon at 85.1 %. However, both materials show significant effectiveness in reducing conductivity levels. Similarly, for TSS, both types of activated carbon perform exceptionally well, with BPAC achieving a removal efficiency of 90.8 % and Commercial Activated Carbon at 92.4 %. When it comes to heavy metal contaminants like Lead and Cadmium, both activated carbons exhibit impressive removal efficiencies, with BPAC showing 92.4 % and 89.9 % removal efficiency for Lead and Cadmium, respectively, while Commercial Activated Carbon achieves slightly higher removal efficiencies of 97.6 % for Lead and 91.6 % for Cadmium.

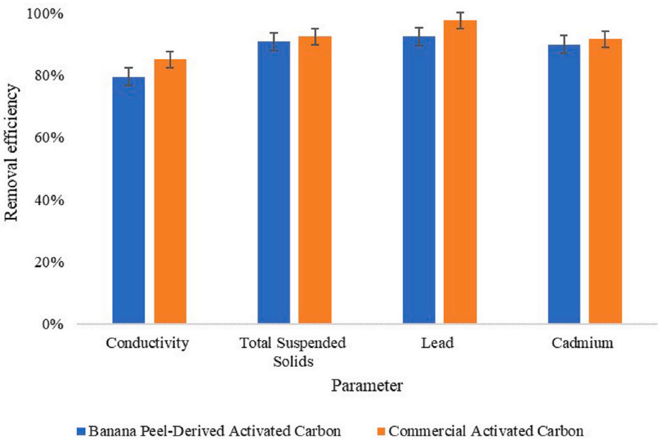


Fig. 2. Removal efficiency of the investigated materials for real wastewater.

3.3. Adsorption capacity and removal efficiency with pH adjustment

The results from Table 3 and Fig. 3 illustrate the adsorption characteristics of both BPAC and commercial activated carbon across various pH levels. Generally, commercial activated carbon exhibits slightly higher adsorption capacities and percentage removal efficiencies compared to BPAC. For instance, at pH 7, commercial activated carbon displays a mean adsorption capacity of 5.80 ± 0.24 mg/g for lead (Pb) and 4.25 ± 0.21 mg/g for cadmium (Cd), with corresponding percentage removal values of 90.5 ± 2.4 % and 82.4 ± 2.1 %, respectively. In contrast, at the same pH, BPAC demonstrates a mean adsorption capacity of 4.95 ± 0.21 mg/g for Pb and 3.68 ± 0.19 mg/g for Cd, with percentage removal values of 84.2 ± 2.1 % and 78.9 ± 2.0 %, respectively. Similarly, at pH 8, commercial activated carbon exhibits a mean adsorption capacity of 5.40 ± 0.23 mg/g for Pb and 3.95 ± 0.20 mg/g for Cd, with corresponding percentage removal values of 87.8 ± 2.3 % and 80.8 ± 2.0 %, while BPAC shows slightly lower values with a mean adsorption capacity of 4.70 ± 0.20 mg/g for Pb and 3.45 ± 0.18 mg/g for Cd, and percentage removal values of 81.6 ± 2.0 % and 75.5 ± 1.8 %, respectively. Interestingly, it was observed that at a low pH of 4, BPAC exhibited a notable increase in adsorption capacity, with values of 5.50 ± 0.20 for lead (Pb) and 4.10 ± 0.15 for cadmium (Cd). In comparison, the commercial activated carbon showed slightly lower values at the same pH, with 5.20 ± 0.25 for Pb and 3.90 ± 0.20 for Cd. These findings suggest that while commercial activated carbon tends to outperform BPAC, both materials demonstrate effective heavy metal adsorption capabilities across various pH conditions, with BPAC offering competitive performance, particularly considering its cost-effectiveness and environmentally sustainable nature.

Table 2
BET analysis results.

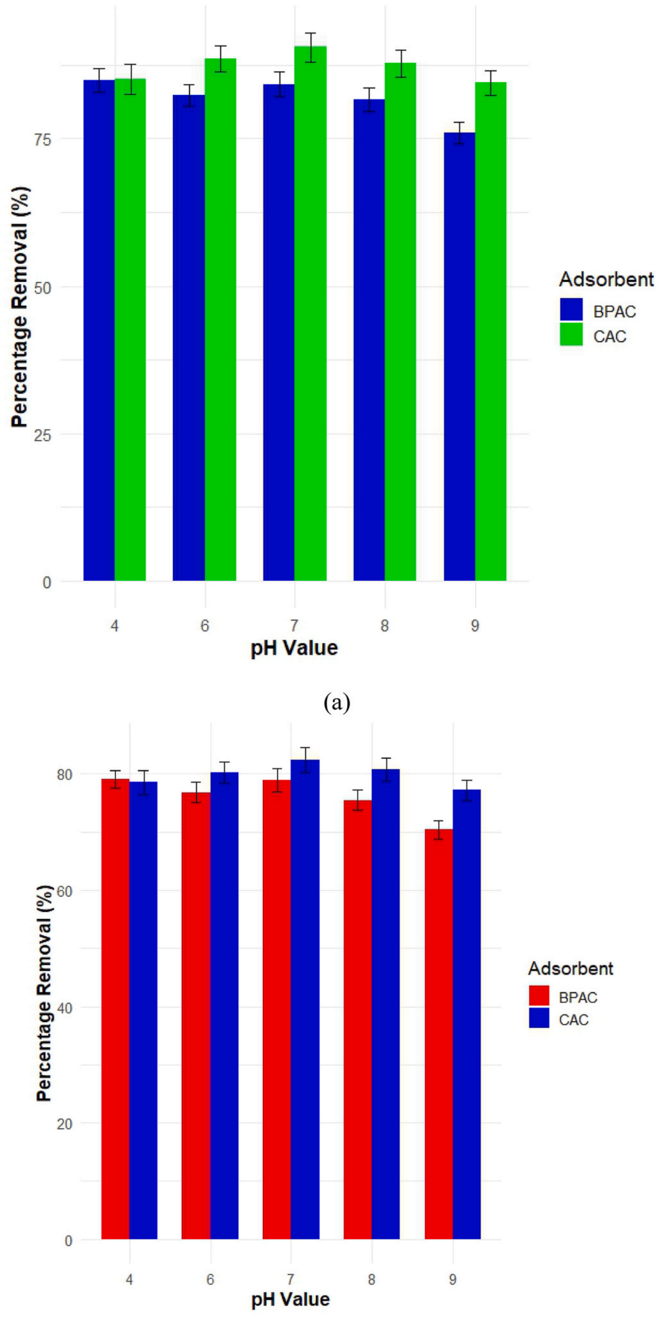
Adsorbent	Surface Area (m^2/g) ± SD	Pore Volume (cm^3/g) ± SD	Pore Diameter (nm) ± SD	Total Micropore Volume (cm^3/g) ± SD	Total Mesopore Volume (cm^3/g) ± SD
BPAC	841 ± 20	0.47 ± 0.02	2.1 ± 0.1	0.26 ± 0.028	0.20 ± 0.01
Commercial Activated Carbon	953 ± 25	0.52 ± 0.03	2.5 ± 0.2	0.33 ± 0.031	0.20 ± 0.02

Table 3
Adsorption Capacity at Different pH Values.

Adsorbent	pH Value	Adsorption Capacity (Pb) (mg/g) ± SD	Adsorption Capacity (Cd) (mg/g) ± SD
BPAC	4	5.50 ± 0.20	4.10 ± 0.15
Commercial Activated Carbon		5.20 ± 0.25	3.90 ± 0.20
BPAC	6	4.82 ± 0.18	3.56 ± 0.17
Commercial Activated Carbon		5.60 ± 0.22	4.10 ± 0.18
BPAC	7	4.95 ± 0.21	3.68 ± 0.19
Commercial Activated Carbon		5.80 ± 0.24	4.25 ± 0.21
BPAC	8	4.70 ± 0.20	3.45 ± 0.18
Commercial Activated Carbon		5.40 ± 0.23	3.95 ± 0.20
BPAC	9	4.35 ± 0.19	3.20 ± 0.16
Commercial Activated Carbon		5.00 ± 0.21	3.70 ± 0.17

3.4. Adsorption capacity and removal efficiency with adsorbent dosage adjustment

The results from Table 4 and Fig. 4 depict the adsorption capacity and percentage removal of lead (Pb) and cadmium (Cd) by both BPAC and commercial activated carbon at different dosages. Overall, an increase in dosage leads to a corresponding increase in adsorption capacity and percentage removal for both adsorbents. For instance, at a dosage of 1 g/L, BPAC demonstrates an adsorption capacity of 3.20 ± 0.15 mg/g for Pb and 2.45 ± 0.12 mg/g for Cd, with percentage removal values of 68.9 ± 1.5 % and 61.3 ± 1.2 %, respectively. In comparison,



(a)

(b)

Fig. 3. Percentage Removal at Different pH Values (a) Pb (c) Cd.

commercial activated carbon exhibits slightly higher adsorption capacities and percentage removal efficiencies at the same dosage. At higher dosages of 5 g/L and 10 g/L, both BPAC and commercial activated carbon show substantial improvements in adsorption capacity and percentage removal for both Pb and Cd. For instance, at a dosage of 10 g/L, BPAC demonstrates an impressive adsorption capacity of 6.10 ± 0.25 mg/g for Pb and 4.82 ± 0.22 mg/g for Cd, with corresponding percentage removal values of 90.2 ± 2.5 % and 85.6 ± 2.2 %, respectively. Similarly, commercial activated carbon exhibits enhanced performance at higher dosages, with adsorption capacities and percentage removal values surpassing those of BPAC. These results underscore the importance of dosage optimization in maximizing the adsorption efficiency of both BPAC and commercial activated carbon for the removal of heavy metals from wastewater.

Table 4
Adsorption capacity and percentage removal at different dosages.

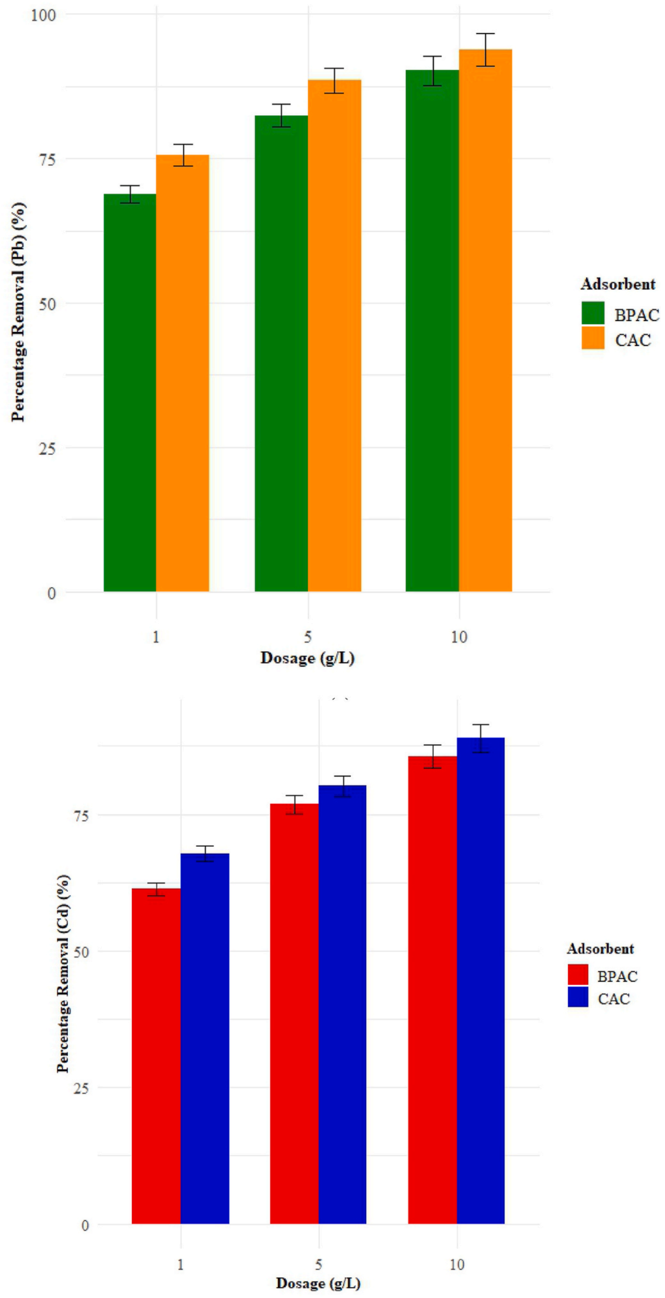
Adsorbent	Dosage (g/L)	Adsorption Capacity (Pb) (mg/g) ± SD	Adsorption Capacity (Cd) (mg/g) ± SD
BPAC	1	3.20 ± 0.15	2.45 ± 0.12
Commercial Activated Carbon		3.80 ± 0.18	2.90 ± 0.15
BPAC	5	4.82 ± 0.20	3.56 ± 0.18
Commercial Activated Carbon		5.60 ± 0.22	4.10 ± 0.20
BPAC	10	6.10 ± 0.25	4.82 ± 0.22
Commercial Activated Carbon		7.20 ± 0.28	5.20 ± 0.25

3.5. *Adsorption kinetics and isotherms*

The results presented in Table 5 reveal the kinetic parameters, specifically the pseudo-first-order rate constant (k_1) and pseudo-second-order rate constant (k_2), for the adsorption of lead (Pb) and cadmium (Cd) by both BPAC and commercial activated carbon at different dosages. Generally, an increase in dosage leads to an increase in both k1 and k_2 values for both adsorbents, indicating enhanced adsorption kinetics with higher dosages. For instance, at a dosage of 1 g/L, BPAC exhibits a pseudo-first-order rate constant (k_1) of 0.011 ± 0.001 min^{-}1 and a pseudo-second-order rate constant (k_2) of 0.0012 ± 0.0001 g/(mg·min), while commercial activated carbon shows slightly higher values with k1 of 0.012 ± 0.001 min^{-1} and k_2 of 0.0013 ± 0.0001 g/(mg·min). Similarly, at dosages of 5 g/L and 10 g/L, both BPAC and commercial activated carbon demonstrate increased k1 and k_2 values, indicating faster adsorption kinetics at higher dosages. Notably, commercial activated carbon consistently exhibits slightly higher rate constants compared to BPAC across all dosages, suggesting its slightly superior adsorption kinetics for Pb and Cd removal. These findings highlight the influence of dosage on the adsorption kinetics of both adsorbents and underscore the importance of optimizing dosage to enhance the efficiency of heavy metal removal from wastewater.

The results from Table 6 outline the isotherm parameters, including the Langmuir maximum adsorption capacity (q_{max}), Langmuir equilibrium constant (K_L), and Freundlich constant (K_F), for the adsorption of lead (Pb) and cadmium (Cd) by both BPAC and commercial activated carbon at different pH values. Overall, both adsorbents demonstrate comparable trends in their adsorption behavior across varying pH levels. At each pH value tested, commercial activated carbon consistently exhibits slightly higher Langmuir maximum adsorption capacities (q_{max}) compared to BPAC, indicating its ability to adsorb a greater amount of Pb and Cd per unit mass of adsorbent. For instance, at pH 7, commercial activated carbon demonstrates a Langmuir maximum adsorption capacity of 11.00 ± 0.45 mg/g for Pb, while BPAC shows a slightly lower value of 10.10 ± 0.40 mg/g. Similarly, the Langmuir equilibrium constants (K_L) for commercial activated carbon are slightly higher than those for BPAC at each pH, indicating stronger adsorption affinity towards Pb and Cd ions. However, both adsorbents display similar trends in Freundlich constants (K_F), suggesting comparable adsorption heterogeneity. These findings suggest that while commercial activated carbon generally exhibits slightly superior adsorption capacities and affinities compared to BPAC across different pH conditions, both materials remain effective for the removal of heavy metals from wastewater, with BPAC offering competitive performance and demonstrating potential as a cost-effective and environmentally sustainable alternative.

The results from Table 7 depict the adsorption kinetics over time for lead (Pb) and cadmium (Cd) by both BPAC and commercial activated carbon. Generally, an increase in adsorption capacity is observed for both adsorbents with longer contact times. For instance, at 30 minutes, BPAC exhibited an adsorption capacity of 3.50 ± 0.15 mg/g for Pb,



(b)

Fig. 4. Percentage removal at different dosages (a) Pb (c) Cd.

which increased to 4.80 ± 0.22 mg/g at 120 minutes. A similar trend is observed for commercial activated carbon, where the adsorption capacity for Pb increased from 3.80 ± 0.18 mg/g at 30 minutes to 5.10 ± 0.25 mg/g at 120 minutes. This indicates that the adsorption process is time-dependent, with longer contact times allowing for more substantial interaction between the adsorbent and the heavy metal ions present in the wastewater. The higher adsorption capacities observed at longer contact times suggest that extended treatment durations may be beneficial for maximizing the removal of Pb and Cd from wastewater using both BPAC and commercial activated carbon, thereby enhancing the efficiency of the wastewater treatment process. The findings underscore the importance of optimizing contact time in adsorption processes to achieve higher removal efficiencies of toxic metals from contaminated water sources.

Table 5
Kinetic parameters at different dosages.

Adsorbent	Dosage (g/L)	Pseudo-first-order rate constant (k_1) (min^{-1}) ± SD	Pseudo-second-order rate constant (k_2) (g/(mg·min)) ± SD
BPAC	1	0.011 ± 0.001	0.0012 ± 0.0001
Commercial Activated Carbon		0.012 ± 0.001	0.0013 ± 0.0001
BPAC	5	0.015 ± 0.001	0.0020 ± 0.0001
Commercial Activated Carbon		0.017 ± 0.001	0.0021 ± 0.0001
BPAC	10	0.020 ± 0.002	0.0025 ± 0.0002
Commercial Activated Carbon		0.022 ± 0.002	0.0028 ± 0.0002

Table 6
Isotherm parameters at different pH values.

Adsorbent	pH Value	Langmuir maximum adsorption capacity (q_{max}) (mg/g) ± SD	Langmuir equilibrium constant (K_L) (L/mg) ± SD	Freundlich constant (KF) ((mg/g)/(mg/L)$^{(1/n)}$) ± SD
BPAC	4	9.20 ± 0.40	0.049 ± 0.002	2.20 ± 0.10
Commercial Activated Carbon		10.00 ± 0.45	0.052 ± 0.003	2.35 ± 0.12
BPAC	6	9.75 ± 0.38	0.052 ± 0.002	2.34 ± 0.11
Commercial Activated Carbon		10.50 ± 0.42	0.055 ± 0.003	2.48 ± 0.13
BPAC	7	10.10 ± 0.40	0.055 ± 0.002	2.48 ± 0.11
Commercial Activated Carbon		11.00 ± 0.45	0.058 ± 0.003	2.60 ± 0.12
BPAC	8	9.50 ± 0.42	0.050 ± 0.002	2.30 ± 0.10
Commercial Activated Carbon		10.20 ± 0.40	0.053 ± 0.002	2.40 ± 0.11
BPAC	9	8.80 ± 0.38	0.047 ± 0.002	2.10 ± 0.09
Commercial Activated Carbon		9.60 ± 0.42	0.050 ± 0.002	2.20 ± 0.10

Table 7
Adsorption kinetics over time.

Adsorbent	Time (min)	Adsorption Capacity (Pb) (mg/g) ± SD	Adsorption Capacity (Cd) (mg/g) ± SD
BPAC	30	3.50 ± 0.15	2.60 ± 0.12
Commercial Activated Carbon		3.80 ± 0.18	2.90 ± 0.15
BPAC	60	4.20 ± 0.20	3.10 ± 0.16
Commercial Activated Carbon		4.50 ± 0.22	3.30 ± 0.18
BPAC	120	4.80 ± 0.22	3.50 ± 0.20
Commercial Activated Carbon		5.10 ± 0.25	3.80 ± 0.22

Table 8
p-values from *t*-test analysis.

Parameter	p-value	Status
EC	0.042	Significant
TSS	0.251	Not significant
Pb	0.013	Significant
Cd	0.105	Not significant

The statistical analysis comparing the removal efficiencies of BPAC and Commercial Activated Carbon across various parameters revealed differing outcomes (Table 8). Notably, Pb concentration, the *t*-test yielded a significant p-value of 0.013, indicating a statistically significant difference in removal efficiency between BPAC and Commercial Activated Carbon treatments. Conversely, the comparison for EC resulted in a p-value of 0.042, suggesting a significant difference as well. However, no significant differences were observed in the removal efficiencies of TSS (p-value = 0.251) or Cd concentration (p-value = 0.105) between the two carbon types. These findings suggest that while BPAC and Commercial Activated Carbon demonstrate similar effectiveness in certain aspects of wastewater treatment, disparities exist in their efficacy for specific contaminants, notably lead, potentially influencing the selection of the most appropriate adsorbent material for targeted contaminant removal in industrial wastewater treatment processes.

3.6 Removal efficiency comparative Table 9 compares the heavy metal removal efficiencies of various materials, highlighting both results from this study and findings from other research. In this study, banana peel-derived activated carbon effectively removes lead and cadmium with efficiencies of 92.4 % and 89.9 %, respectively, while commercial activated carbon shows slightly higher efficiencies for these metals at 97.6 % and 91.6 %. Other studies report 80 % chromium removal with acrylonitriledivinylbenzene copolymer and only 28 % with tamarind wood. For iron, rice husk shows a broad efficiency range (68.59 %–99.25 %), whereas fly ash ranges from 46.18 % to 86.757 %. Lead removal with rice husk and fly ash varies widely, between 22.22 % to 87.17 % and 21.79 %–76.06 %, respectively. *Zizania caduciflora* achieves 84.8 % chromium removal, and raw kaolinite shows 63.37 % and 69.23 % removal efficiencies for nickel and copper, respectively, which improve to 68.32 % and 77.47 % with acid activation. This comparative analysis highlights the relative effectiveness of banana peel-derived activated carbon and commercial activated carbon over other materials.

4. Discussion

The BET analysis results revealed significant disparities in the porous characteristics between BPAC and commercial activated carbon, which profoundly influenced their adsorption performance. Despite both materials boasting substantial surface areas, with BPAC measuring 841 ± 20 m^2/g and commercial activated carbon measuring 953 ± 25 m^2/g, the latter exhibited a slightly higher surface area, potentially indicating a greater adsorption capacity. Additionally, the larger pore volume of commercial activated carbon (0.52 ± 0.03 cm^3/g) compared to BPAC (0.47 ± 0.02 cm^3/g) suggested that it may have had an advantage in accommodating adsorbates. The greater average pore diameter of commercial activated carbon (2.5 ± 0.2 nm) further contributed to its potential superiority, allowing for the adsorption of larger molecules. However, BPAC demonstrated a marginally higher total micropore volume (0.26 ± 0.028 cm^3/g) compared to commercial activated carbon (0.33 ± 0.031 cm^3/g), indicating a higher proportion of micropores available for adsorption. Micropores are known for their enhanced adsorption capacity due to increased surface interactions [30], suggesting that BPAC may have excelled in capturing smaller molecules, such as heavy metal ions, thereby offering competitive performance in wastewater treatment applications despite its slightly inferior porous characteristics.

Table 9
Removal efficiency comparative analysis.

Material	Heavy metal	Removal efficiny (%)	Source
Banana Peel-Derived Activated Carbon	Lead	92.4	This study
	Cadmium	89.9	This study
Commercial Activated Carbon	Lead	97.6	This study
	Cadmium	91.6	This study
Acrylonitriledivinylbenzene copolymer	Chromium	80	[25]
rice husk	Iron	68.59 to 99.25	[26]
fly Ash	Iron	46.18 to 86.757	[26]
Tamarind wood	Chromium	28	[27]
removal with rice husk	Lead	22.22 to 87.17	[26]
fly Ash	Lead	21.79 to 76.06	[26]
Zizania caduciflora	Chromium	84.8	[28]
raw kaolinite	Nickel	63.37	[29]
	Copper	69.23	[29]
acid activated kaolinite	Nickel	68.32	[29]
	Copper	77.47	[29]

The observed removal efficiencies of both BPDAC and CAC can be attributed to several underlying mechanisms governing contaminant adsorption. In the case of conductivity reduction, activated carbons possess a high surface area and pore structure, providing ample sites for the adsorption of ions present in water, thereby reducing conductivity levels. Both BPDAC and CAC exhibit this property, albeit with slight variations in efficiency, likely due to differences in pore size distribution and surface chemistry. For TSS removal, activated carbons can physically adsorb suspended particles through mechanisms such as pore-filling and surface adsorption, leading to the observed high removal efficiencies for both materials. When it comes to heavy metal contaminants like Lead and Cadmium, the removal process is predominantly governed by chemisorption, where metal ions form strong bonds with functional groups on the activated carbon surface. Both BPDAC and CAC possess functional groups capable of binding heavy metal ions effectively, resulting in the high removal efficiencies observed. The slight variations in removal efficiencies between the two materials could be attributed to differences in surface chemistry, specific surface area, and pore structure, which influence the adsorption capacity and kinetics. The results highlight the effectiveness of both BPDAC and CAC in water treatment applications, underscoring the importance of understanding the underlying mechanisms governing contaminant adsorption for optimizing treatment processes. Renu et al. [31], suggest that activated carbon proves effective in eliminating heavy metals such as chromium due to its extensive porous structure and significant internal surface area, facilitating adsorption. Typically, the removal efficiency outcomes align with findings reported from various other studies, including those by Ali et al. [32], Charazińska et al. [33], Dharmapriya et al. [34], Irfan et al. [35], Yimer et al. [36], Ahmed et al. [37], among others.

Also, the results revealed notable differences in the adsorption characteristics between BPAC and commercial activated carbon across various pH levels. CAC consistently exhibited slightly higher adsorption capacities and percentage removal efficiencies compared to BPAC across the tested pH range. This superiority could be attributed to its larger surface area and pore volume, allowing for more extensive interactions with heavy metal ions. Specifically, at pH 7 and 8, commercial activated carbon demonstrated mean adsorption capacities for Pb and Cd that were higher than those of BPAC, indicating its enhanced affinity for heavy metal adsorption under neutral to slightly alkaline conditions. However, despite these differences, both adsorbents showed effective heavy metal removal capabilities across the pH spectrum, with BPAC offering competitive performance, particularly considering its cost-effectiveness and eco-friendly nature. In the research led by Kaya et al., tartaric acid was employed to enhance wheat bran, yielding significant improvements in chromium removal efficiency. Prior to modification, a removal rate of 51 % was observed, whereas post-modification, removal soared to 90 % at a pH of 2. Furthermore, the study revealed notable increases in the maximum adsorption capacity, reaching 4.53 mg of Cr(VI)/g without modification and 5.28 mg of Cr (VI)/g with modification, particularly at a pH of 2.2.

While, the results from the adsorption experiments demonstrated a clear relationship between dosage and the adsorption capacity of both BPAC and CAC for the removal of lead (Pb) and cadmium (Cd) from wastewater. As the dosage increased, there was a corresponding enhancement in both adsorption capacity and percentage removal for both adsorbents. At lower dosages, BPAC exhibited respectable adsorption capacities and percentage removal efficiencies, although slightly lower compared to commercial activated carbon. For example, at a dosage of 1 g/L, BPAC showed adsorption capacities of 3.20 ± 0.15 mg/g for Pb and 2.45 ± 0.12 mg/g for Cd, with percentage removal values of 68.9 ± 1.5 % and 61.3 ± 1.2 %, respectively. However, at higher dosages (5 g/L and 10 g/L), both BPAC and commercial activated carbon demonstrated remarkable improvements in adsorption performance, with BPAC achieving an impressive adsorption capacity of 6.10 ± 0.25 mg/g for Pb and 4.82 ± 0.22 mg/g for Cd at a dosage of 10 g/L, along with percentage removal values of 90.2 ± 2.5 % and 85.6 ± 2.2 %, respectively. Commercial activated carbon also exhibited enhanced performance at higher dosages, surpassing the adsorption capacities and percentage removal values of BPAC. These findings underscore the significance of dosage optimization in maximizing the adsorption efficiency of both BPAC and commercial activated carbon, highlighting their potential for effective removal of heavy metals from wastewater streams [38].

The kinetic parameters, specifically the pseudo-first-order rate constant (k_1) and pseudo-second-order rate constant (k_2), were analyzed for the adsorption of lead (Pb) and cadmium (Cd) by both BPAC and commercial activated carbon at different dosages. An increase in dosage corresponded to higher k_1 and k_2 values for both adsorbents, indicating improved adsorption kinetics with increased dosages. For instance, at a dosage of 1 g/L, BPAC exhibited a pseudo-first-order rate constant (k_1) of 0.011 ± 0.001 min^{-1} and a pseudo-second-order rate constant (k_2) of 0.0012 ± 0.0001 g/(mg·min), while commercial activated carbon showed slightly higher values with k_1 of 0.012 ± 0.001 min^{-1} and k_2 of 0.0013 ± 0.0001 g/(mg·min). Similarly, at dosages of 5 g/L and 10 g/L, both BPAC and commercial activated carbon demonstrated increased k_1 and k_2 values, indicating faster adsorption kinetics at higher dosages. Notably, commercial activated carbon consistently exhibited slightly higher rate constants compared to BPAC across all dosages, suggesting its slightly superior adsorption kinetics for Pb and Cd removal. In the study conducted by Elkhaleefa et al. [39], focusing on the utilization of Azadirachta indica leaves as an adsorbent for removing Lead(II) ions from aqueous solutions. Batch experiments were conducted to investigate the impact of particle size, pH, adsorbent dosage, contact time, initial Pb(II) ion concentration, and temperature. A maximum removal efficiency of 93.5 % was attained from a starting Pb(II) ion concentration of 50 mg/L within 40 minutes, at pH 7, using an adsorbent dose of 0.60 g.

The isotherm parameters, including Langmuir maximum adsorption capacity ($q_{ma}x$), Langmuir equilibrium constant (K_L), and Freundlich constant (K_F), were analyzed for the adsorption of Pb and Cd by BPAC and commercial activated carbon at different pH values. Commercial activated carbon consistently exhibited slightly higher Langmuir maximum adsorption capacities (q_{max}) compared to BPAC at each pH level, indicating its ability to adsorb a greater amount of Pb and Cd per unit mass of adsorbent. Additionally, the Langmuir equilibrium constants (K_L) for commercial activated carbon were slightly higher than those for BPAC at each pH, suggesting stronger adsorption affinity towards Pb and Cd ions. However, both adsorbents displayed similar trends in Freundlich constants (K_F), indicating comparable adsorption heterogeneity. Moreover, the observed results indicated a time-dependent trend in the adsorption kinetics of lead (Pb) and cadmium (Cd) by both BPAC and commercial activated carbon. A consistent increase in adsorption capacity was noted for both adsorbents with longer contact times. For instance, at 30 minutes, BPAC exhibited an adsorption capacity of 3.50 ± 0.15 mg/g for Pb, which increased to 4.80 ± 0.22 mg/g at 120 minutes. Similarly, commercial activated carbon showed an increase in Pb adsorption capacity from 3.80 ± 0.18 mg/g at 30 minutes to 5.10 ± 0.25 mg/g at 120 minutes. This trend suggested that prolonged contact times allowed for more substantial interaction between the adsorbent and the heavy metal ions in the wastewater, leading to higher adsorption capacities. Therefore, extending treatment durations could potentially enhance the efficiency of Pb and Cd removal from wastewater using both BPAC and commercial activated carbon, highlighting the time-dependent nature of the adsorption process in wastewater treatment applications.

5. Conclusion

The study investigated the effectiveness of BPAC alongside commercial activated carbon for removing heavy metals from industrial wastewater. Testing at various pH levels showed both materials had competitive adsorption capacities, with typical lead (Pb) removal ranging from 4 to 6 mg/g and cadmium (Cd) from 3 to 5 mg/g. While both materials had substantial surface areas, commercial activated carbon had a slightly higher surface area (953 ± 25 m^2/g) compared to BPAC (841 ± 20 m^2/g), indicating potentially greater adsorption capacity. Additionally, commercial activated carbon had a larger pore volume (0.52 ± 0.03 cm^3/g) and average pore diameter (2.5 ± 0.2 nm), suggesting an advantage in accommodating adsorbates. However, BPAC showed a slightly higher total micropore volume (0.26 ± 0.028 cm^3/g), indicating more micropores available for adsorption. Commercial activated carbon generally exhibited slightly better adsorption kinetics, but BPAC remained a cost-effective option with removal efficiencies typically ranging from 75 % to 90 %. Across different pH levels, commercial activated carbon consistently showed slightly higher adsorption capacities and percentage removal efficiencies compared to BPAC. This superiority was attributed to its larger surface area and pore volume, allowing for more extensive interactions with heavy metal ions, especially under neutral to slightly alkaline conditions. Despite differences, both adsorbents effectively removed heavy metals across the pH spectrum, with BPAC offering competitive performance considering its cost-effectiveness and eco-friendly nature. Optimizing dosage was crucial for maximizing removal efficiency, and extended contact times were essential for enhanced removal. The study contributes to sustainable wastewater treatment methods, providing practical solutions to address heavy metal contamination in industrial effluents. Generally, the study endeavors to conduct a comprehensive comparison between Banana Peel-Derived Activated Carbon and commercially available activated carbon in their efficacy for heavy metal removal from industrial wastewater. However, it is essential to acknowledge a potential limitation concerning the variability of outcomes, attributable to inherent differences in the properties of activated carbon batches and the diverse composition of industrial wastewater samples. Future research could focus on further optimization, scale-up efforts, and exploring BPAC's applicability in various wastewater treatment scenarios to advance environmental sustainability and mitigate the adverse impacts of heavy metal contamination.

CRediT authorship contribution statement

Timoth Mkilima: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Yerkebulan Zharkenov:** Resources, Project administration, Investigation, Funding acquisition. **Aisulu Abduova:** Resources, Investigation. **Nursulu Sarypbekova:** Resources, Investigation. **Nurlan Kudaibergenov:** Resources, Investigation. **Kuandyk Sakanov:** Investigation, Resources. **Gyulnara Zhukenova:** Resources, Investigation. **Zhumabek Omarov:** Resources, Investigation. **Parida Sultanbekova:** Resources, Investigation. **Gulmira Kenzhaliyeva:** Resources, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] W. Jadaa, H. Mohammed, Heavy metals – definition, natural and anthropogenic sources of releasing into ecosystems, toxicity, and removal methods – an overview study, J. Ecol. Eng. 24 (2023) 249–271, https://doi.org/10.12911/22998993/162955.

[2] M.P. Wagh, Y. Aher, A. Mandalik, Potential of moringa oleifera seed as a natural adsorbent for wastewater treatment, Trends Sci 19 (2022) 2019, https://doi.org/10.48048/tis.2022.2019.

[3] H. Sukmana, N. Bellahsen, F. Pantoja, C. Hodur, Adsorption and coagulation in wastewater treatment - review, Prog. Agric. Eng. Sci. (2021), https://doi.org/10.1556/446.2021.00029.

[4] C. Zhao, J. Zhou, Y. Yan, L. Yang, G. Xing, H. Li, P. Wu, M. Wang, H. Zheng, Application of coagulation/flocculation in oily wastewater treatment: a review, Sci. Total Environ. 765 (2021) 142795, https://doi.org/10.1016/j.scitotenv.2020.142795.

[5] S. Kosar, O. Isik, B. Cicekalan, H. Gulhan, E. Sagir Kurt, E. Atli, S. Basa, H. Ozgun, I. Koyuncu, M.C.M. van Loosdrecht, M.E. Ersahin, Impact of primary sedimentation on granulation and treatment performance of municipal wastewater by aerobic granular sludge process, J. Environ. Manag. 315 (2022) 115191, https://doi.org/10.1016/j.jenvman.2022.115191.

[6] M. Oh, K. Lee, M.K. Jeon, R.I. Foster, C.-H. Lee, Chemical precipitation–based treatment of acidic wastewater generated by chemical decontamination of radioactive concrete, J. Environ. Chem. Eng. 11 (2023) 110306, https://doi.org/10.1016/j.jece.2023.110306.

[7] K. Meiramkulova, D. Devrishov, M. Zhumagulov, S. Arystanova, Z. Karagoishin, S. Marzanova, A. Kydyrbekova, T. Mkilima, J. Li, Performance of an integrated membrane process with electrochemical pre-treatment on poultry slaughterhouse wastewater purification, Membranes 10 (2020) 256, https://doi.org/10.3390/membranes10100256.

[8] J. Li, Y. Liu, J. Wang, Y. Liu, M. Zhang, L. Zhao, S. Gu, R. Lin, L. Chen, Research progress on the application of natural adsorbents in the treatment of livestock wastewater, Desalination Water Treat. (2024), https://doi.org/10.1016/j.dwt.2024.100018.

[9] T. Mkilima, Y. Sabitov, Z. Shakhmov, T. Abilmazhenov, A. Tlegenov, A. Jumabayev, A. Turashev, Z. Kaliyeva, L. Utepbergenova, Exploring the potential of biofunctionalized agricultural waste adsorbents integrated with UV-LED disinfection for enhanced wastewater treatment, Case Stud. Chem. Environ. Eng. 9 (2024) 100691, https://doi.org/10.1016/j.cscee.2024.100691.

[10] N. Karić, A.S. Maia, A. Teodorović, N. Atanasova, G. Langergraber, G. Crini, A.R. L. Ribeiro, M. Đolić, Bio-waste valorisation: agricultural wastes as biosorbents for removal of (in)organic pollutants in wastewater treatment, Chem. Eng. J. Adv. 9 (2022) 100239, https://doi.org/10.1016/j.ceja.2021.100239.

[11] J. Alam, A.K. Shukla, F.A.A. Ali, O. Daoud, M. Alhoshan, Natural polymer-based sustainable adsorbents for pharmaceutical wastewater treatment, in: Treat. Pharm. Wastewater Innov. Technol. Adapt., 2023, https://doi.org/10.1016/B978-0-323-99160-5.00007-2. Treat. Syst.

[12] H. Gholamifard, M.G. Rasul, H. Rahideh, A. Azari, M. Abbasi, R. Karami, Experimental and numerical analysis of oily wastewater treatment using low-cost mineral adsorbent in a single and multi-fixed bed column, Chem. Eng. J. Adv. 16 (2023) 100551, https://doi.org/10.1016/j.ceja.2023.100551.

[13] F.A. Ahmad, The use of agro-waste-based adsorbents as sustainable, renewable, and low-cost alternatives for the removal of ibuprofen and carbamazepine from water, Heliyon (2023) 105271, https://doi.org/10.1016/j.heliyon.2023.e16449.

[14] I.M. Militao, F.A. Roddick, R. Bergamasco, L. Fan, Removing PFAS from aquatic systems using natural and renewable material-based adsorbents: a review, J. Environ. Chem. Eng. 9 (2021) 105271, https://doi.org/10.1016/j.jece.2021.105271.

[15] L. Li, L. Fan, M. Sun, H. Qiu, X. Li, H. Duan, C. Luo, Adsorbent for chromium removal based on graphene oxide functionalized with magnetic cyclodextrin–chitosan, Colloids Surfaces B Biointerfaces 107 (2013) 76–83, https://doi.org/10.1016/j.colsurfb.2013.01.074.

[16] S.-F. Lo, S.-Y. Wang, M.-J. Tsai, L.-D. Lin, Adsorption capacity and removal efficiency of heavy metal ions by Moso and Ma bamboo activated carbons, Chem. Eng. Res. Des. 90 (2012) 1397–1406, https://doi.org/10.1016/j.cherd.2011.11.020.

[17] C. Luo, Z. Tian, B. Yang, L. Zhang, S. Yan, Manganese dioxide/iron oxide/acid oxidized multi-walled carbon nanotube magnetic nanocomposite for enhanced hexavalent chromium removal, Chem. Eng. J. (2013), https://doi.org/10.1016/j.cej.2013.08.084.

[18] K.J. Cronje, K. Chetty, M. Carsky, J.N. Sahu, B.C. Meikap, Optimization of chromium(VI) sorption potential using developed activated carbon from sugarcane bagasse with chemical activation by zinc chloride, Desalination 275 (2011) 276–284, https://doi.org/10.1016/j.desal.2011.03.019.

[19] Y.-S. Shen, S.-L. Wang, Y.-M. Tzou, Y.-Y. Yan, W.-H. Kuan, Removal of hexavalent Cr by coconut coir and derived chars – the effect of surface functionality, Bioresour. Technol. 104 (2012) 165–172, https://doi.org/10.1016/j.biortech.2011.10.096.

[20] V. Lugo-Lugo, C. Barrera-Díaz, F. Ureña-Núñez, B. Bilyeu, I. Linares-Hernández, Biosorption of Cr(III) and Fe(III) in single and binary systems onto pretreated orange peel, J. Environ. Manag. 112 (2012) 120–127, https://doi.org/10.1016/j.jenvman.2012.07.009.

[21] M. Musah, Y. Azeh, J. Mathew, M. Umar, Z. Abdulhamid, A. Muhammad, Adsorption kinetics and isotherm models: a review, Caliphate J. Sci. Technol. 4 (2022) 20–26, https://doi.org/10.4314/cajost.v4i1.3.

[22] R. Ezzati, Derivation of pseudo-first-order, pseudo-second-order and modified pseudo-first-order rate equations from Langmuir and Freundlich isotherms for adsorption, Chem. Eng. J. 392 (2020) 123705, https://doi.org/10.1016/j.cej.2019.123705.

[23] H. Tun, C.-C. Chen, Isosteric heat of adsorption from thermodynamic Langmuir isotherm, Adsorption 27 (2021) 979–989, https://doi.org/10.1007/s10450-020-00296-3.

[24] M. Vigdorowitsch, A. Pchelintsev, L. Tsygankova, E. Tanygina, Freundlich isotherm: an adsorption model complete framework, Appl. Sci. 11 (2021) 8078, https://doi.org/10.3390/app11178078.

[25] D. Duranoğlu, A.W. Trochimczuk, Ü. Beker, A comparison study of peach stone and acrylonitrile-divinylbenzene copolymer based activated carbons as chromium(VI) sorbents, Chem. Eng. J. 165 (2010) 56–63, https://doi.org/10.1016/j.cej.2010.08.054.

[26] H.A. Hegazi, Removal of heavy metals from wastewater using agricultural and industrial wastes as adsorbents, HBRC J (2013), https://doi.org/10.1016/j.hbrcj.2013.08.004.

[27] J. Acharya, J.N. Sahu, B.K. Sahoo, C.R. Mohanty, B.C. Meikap, Removal of chromium(VI) from wastewater by activated carbon developed from Tamarind wood activated with zinc chloride, Chem. Eng. J. (2009), https://doi.org/10.1016/j.cej.2008.11.035.

[28] H. Liu, S. Liang, J. Gao, H.H. Ngo, W. Guo, Z. Guo, J. Wang, Y. Li, Enhancement of Cr(VI) removal by modifying activated carbon developed from Zizania caduciflora with tartaric acid during phosphoric acid activation, Chem. Eng. J. (2014), https://doi.org/10.1016/j.cej.2014.02.046.

[29] A. Hussain, S. Madan, R. Madan, Removal of heavy metals from wastewater by adsorption, in: Heavy Met. - Their Environ. Impacts Mitig, IntechOpen, 2021, https://doi.org/10.5772/intechopen.95841.

[30] M. Tangsathitkulchai, C. Tangsathitkulchai, K. Wongsooksin, S. Chuyingsakuntip, Removal of residual aluminium-dye complex and aluminium ion from spent natural-dye solution using activated carbons, Eng. J. 16 (2012) 29–44, https://doi.org/10.4186/ej.2012.16.5.29.

[31] M. Agarwal Renu, K. Singh, Heavy metal removal from wastewater using various adsorbents: a review, J. Water Reuse Desalin. 7 (2017) 387–419, https://doi.org/10.2166/wrd.2016.104.

[32] K. Ali, M.U. Javaid, Z. Ali, M.J. Zaghum, Biomass-derived adsorbents for dye and heavy metal removal from wastewater, Adsorpt. Sci. Technol. 2021 (2021), https://doi.org/10.1155/2021/9357509.

[33] S. Charazińska, E. Burszta-Adamiak, P. Lochyński, The efficiency of removing heavy metal ions from industrial electropolishing wastewater using natural materials, Sci. Rep. (2022), https://doi.org/10.1038/s41598-022-22466-9.

[34] T.N. Dharmapriya, D. Li, Y.-C. Chung, P.-J. Huang, Green synthesis of reusable adsorbents for the removal of heavy metal ions, ACS Omega 6 (2021) 30478–30487, https://doi.org/10.1021/acsomega.1c03879.

[35] M. Irfan, A. Arif, M.A. Munir, M.Y. Naz, S. Shukrullah, S. Rahman, M. Jalalah, A.H. M. Almawgani, Statistically analyzed heavy metal removal efficiency of silica-coated Cu0.50Mg0.50Fe2O4 magnetic adsorbent for wastewater treatment, ACS Omega (2023), https://doi.org/10.1021/acsomega.3c05764.

[36] M. Yimer, S.N. Ansari, B.A. Berehe, K.K. Gudimella, G. Gedda, W.M. Girma, N. Hasan, S. Tasneem, Adsorptive removal of heavy metals from wastewater using Cobalt-diphenylamine (Co-DPA) complex, BMC Chem (2024), https://doi.org/10.1186/s13065-024-01128-z.

[37] H.M. Ahmed, N.A. Sobhy, M.M. Hefny, F.M. Abdel-Haleem, M.A. El-Khateeb, Evaluation of agrowaste species for removal of heavy metals from synthetic wastewater, J. Environ. Public Health. 2023 (2023) 1–20, https://doi.org/10.1155/2023/7419015.

[38] D. Nayeri, S.A. Mousavi, Dye removal from water and wastewater by nanosized metal oxides - modified activated carbon: a review on recent researches, J. Environ. Heal. Sci. Eng. 18 (2020) 1671–1689, https://doi.org/10.1007/s40201-020-00566-w.

[39] A. Elkhaleefa, I.H. Ali, E.I. Brima, I. Shigidi, A.B. Elhag, B. Karama, Evaluation of the adsorption efficiency on the removal of lead(II) ions from aqueous solutions using Azadirachta indica leaves as an adsorbent, Processes (2021), https://doi.org/10.3390/pr9030559.