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Research Article

Application of Activated Carbon Derived from *Typha domingensis* in Industrial Wastewater Treatment

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Abstract. Water pollution due to discharge of industrial wastes into aquatic environment remains a major challenge associated with adverse health effects and environmental destruction worldwide. The activated carbon was produced from the plant biosorbent using potassium hydroxide activator method. The activated carbon produced was characterized by surface characteristics and Fourier Transform Infrared (FTIR) spectroscopic technique. The levels of heavy metals in the treated and untreated industrial wastewater sample were determined by atomic absorption spectroscopic (AAS) technique. Batch adsorption study was conducted using the American Public Health Association (APHA) method. The mechanism of heavy metals adsorption capacity of the plant-derived activated carbon was evaluated using Freundlich isotherm and Langmuir isotherm models. The result showed that the plant-derived activated carbon derived exhibited significant ($p < 0.05$) value of surface area (570.33 m^2/g), pore volume (2.56 g/cm^3), pH (6.46), conductivity (64.03 µS/cm), moisture content (20.86 %), and ash content (7.53 %) coupled with low value of porosity (0.82 %), bulk density (0.53 g/cm^3), apparent density (0.32 g/cm^3), and real density (1.91 g/cm^3). The FT-IR spectrum of the activated carbon displayed various band peaks at wavenumber ranged 3350 – 801 cm−1 indicating stretching of C–H, C=O, C–C C–O, and O–H. The untreated wastewater sample demonstrated high significant ($p < 0.05$) amount of cadmium (0.23 mg/L), cobalt (0.83 mg/L), lead (3.02 mg/L), manganese (1.47 mg/L), nickel (0.62 mg/L), and chromium (0.60 mg/L). The plant-derived activated carbon exhibited high significant ($p < 0.05$) percentage efficiency for removal of cadmium (95.55 %), cobalt (96.48 %), lead (97.16 %), manganese (99.25 %), nickel (96.09 %), and chromium (96.88 %) from the industrial wastewater sample. The results of this study showed that the regression coefficient (R^2) values of cadmium, cobalt, lead, manganese, nickel, and chromium for the Langmuir isotherm are higher than that demonstrated by the metals for the Freundlich isotherm model. The experimental equilibrium data for cadmium, cobalt, lead, manganese, nickel, and chromium were best fitted to the Langmuir isotherm model than the Freundlich isotherm model. The activated carbon derived from the roots of *Typha domingensis* demonstrated high adsorption capacity for removal of cadmium, cobalt, lead, manganese, nickel, and chromium from the industrial wastewater.

Keywords: Heavy metals, Industrial wastewater, Phytoremediation, Pollution, *Typha domingensis*.

1. Introduction

Industrial activities remain a major threat to aquatic environment via discharge of wastes including toxic substances into the environment. The sources of water pollution include wastewater discharge from industries, agricultural activities, municipal wastewater, environmental and global changes. However, fertilizer industrial activities and agricultural practices such as pesticide spraying are some of the major causes of water pollution (Kumar et al., 2017). Industrial wastewater contains many organic and inorganic pollutants that have adverse effects on environment, aquatic life, human and animal health (Ahmed et al., 2021; Albatrni et al., 2021). These pollutants including toxic heavy metals and dyes are easily transported and dispersed into surface water resulting to immediate and persistent hazardous concerns. Thus, release of industrial wastewater into the environment should be minimized to control pollution and ensure the safety of the communities.

Conventional wastewater treatment methods such as coagulation, ultra-filtration, electrochemical, advanced oxidation, electrolysis, and photo-catalysis are associated with many challenges. Some of the challenges associated with these methods are generation of toxic sludge, high operational and maintenance costs, and complex operational technique (Yahiaoui et al., 2021). Thus, there is need for effective treatment of wastewater before release to township for consumption and domestic activities. Adsorption technique has been employed in wastewater treatment for removal of organic and inorganic pollutants including heavy metals, dyes, pesticides, fertilizers, phenols, plasticizers, biphenyls, detergents, oils and greases (Wong et al., 2018). Adsorption technique for wastewater treatment is highly effective, less expensive, easy accessible, and simple to design and operate. Researchers have concentrated on the use of adsorption technique in wastewater treatment due to its adaptability, simplicity of design, convenience of use, high capacity to remove pollutants (Qiu et al., 2022; Bhagat et al., 2021).

Natural products particularly plants and agro-wastes have been used as bio-adsorbents (Kumar et al., 2021). Adsorbents derived from plants and agro-wastes demonstrate high capacity for removal of many different contaminants from wastewater (Sivaranjanee & Kumar, 2021). Activated carbon from the natural product adsorbents displayed high potential for wastewater treatment (Ganiyu et al., 2023; Garba et al., 2019). Phytoremediation is a remediation technique that involves the use of plants to remove contaminants from polluted environment (Vázquez-Núñez et al., 2018). Phytoremediation has many advantages which include simplicity, less expensive, and ease of operation and maintenance. However, phytoremediation is safer than conventional treatment methods. Many aquatic plants have reported with exceptional phytoremediation potential.

Typha domingensis is a plant growth in aquatic environment including moist soil, swamps, marshes, lakeshores, roadsides, and manmade reservoirs (Aliyu et al., 2025). The plant is a member of Typhaceae family and Typha genus which comprises several species (Aliyu et al., 2025). *Typha domingensis* is commonly known as cattail and is widely found in tropical and subtropical regions (Sesin et al., 2021; WCSPF 2023). *Typha domingensis* contains powder flour that is used in production of different food products (Aljazy et al., 2021). *Typha domingensis* serves many functions including flood prevention, bank and sediment stability, conservation of natural resources, purification of water, and retention or immobilisation of pollutants (Kennedy et al., 2025). Typha species such *as T. angustifolia, T. dominengensis, T. orientalis*, and T. latifolia have been documented as potential remediators of metals in aquatic environments (Futughe et al., 2020). *Typha domingensis* has been reported with high removal capacity for various pollutants in aquatic environments (Al-Sodany et al., 2021; Sesin et al. 2021; Hadad et al., 2018). *Typha domingensis* contains significant amount of proximate components and other nutrients (Aliyu et al., 2025). This indicates that *Typha domingensis* could be an excellent source of carbon based material. However, the powder flour content of *Typha domingensis* (Aljazy et al., 2021) is an indication of production capacity of *Typha domingensis* for activated carbon. Furthermore, it was predicted that the roots part of *Typha domingensis* could display high heavy metals adsorption capacity than the other parts of the plant.

In Nigeria *Typha domingensis* is locally known as Kachalla or Geron tsuntsu or Shala in Hausa. The plant is abundantly available in almost aquatic areas in North Western zone of Nigeria. In Nigeria, *Typha domingensis* serves as important source of foods and fodder for animals, and raw material for manufacturing useful materials such as boats and stuffing pillows. Although, few studies reported the efficiency of *Typha domingensis* for removal of heavy metals from aquatic environments, no study reported the heavy metals removal efficiency of *Typha domingensis* from industrial wastewater. Also, there was no specific report on heavy metals removal capacity of the roots of *Typha domingensis*. In addition, there was no study reported the heavy metals adsorption capacity of *Typha domingensis* derived activated carbon which has been documented with high heavy metals adsorption capacity than a raw sample of plant or biomass. However, to the best of our knowledge, there is no study reported on the phytoremediation potential of *Typha domingensis* in wastewater in Kebbi state, Nigeria. This study aims at evaluating the adsorption capacity of activated carbon derived from the roots of *Typha domingensis* for removal of heavy metals from the industrial wastewater and elucidating its mechanism of the heavy metal adsorption.

2. Method

2.1. Study Site

This study was conducted in Argungu Emirate in Kebbi State, Nigeria. Argungu Emirate is one of the four traditional states in Kebbi State, Nigeria. The three other local states in Kebbi State are Gwandu Emirate, Yauri Emirate and Zuru Emirate. Argungu Emirate is geographically characterizes by approximately 800 mm mean annual rainfall, 24 % average humidity, and annual average temperature of 33.55 °C (HWD, 2023; ACW, 2023). The 2007 national census showed that Argungu, one of the local government areas in Argungu Emirate recorded a population of approximately 47,064 (TWG, 2007). Argungu is the main agricultural area in Kebbi state producing varieties of crops including peanuts, rice, millet, wheat, and sorghum. Argungu has been a fishing practice area and the town hosts an annual international fishing festival titled "Argungu Fishing Festival". However, the town has been benefiting with the existing of one of the

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largest rice processing industries in Nigeria. The activities of the rice processing industry in the area lead to generation of wastewater specifically discharged into open drainage channels and subsequently into the ground and surface water. This study will help provide information on the need for effective wastewater treatment strategies and pollution control for the safety of the community health and environment.

2.2. Plant Sample

Fresh roots *Typha domingensis* were obtained from moist site of Shagari dam in Shagari local government area, Sokoto state, Nigeria in middle February 2024. The plant roots sample was identified and authenticated at the Herbarium Unit, Department of Plant Science, Usmanu Danfodiyo University, Sokoto and the voucher number (UDUH/ANS/1115) was deposited in the herbarium.

2.3. Wastewater Sample

The wastewater sample was collected from the drainage site of WACOT rice processing industry in Argungu, Kebbi State, Nigeria. The wastewater sample was collected in clean polyethylene plastic bottles and transported on ice to the Laboratory Unit, Department of Science Technology, Waziri Umaru Federal Polytechnic, Birnin Kebbi, Nigeria for analyses.

2.4. Preparation of the Plant Biosorbent

The plant roots samples were thoroughly washed with distilled water to remove sand and other impurities. The roots samples were dried in an oven maintained at 40 °C for 72 hours. The dried roots samples were grounded to fine powder of large size distribution and then sieved using Mesh sieve to obtained biosorbent particles of 45 – 65 μm size range.

2.5. Production of Activated Carbon

The activated carbon was produced from the plant biosorbent according to the method described by Gómez et al. (2022) and Zornitta et al. (2020). The plant powder materials of specific size (45 – 65 μm) was treated with 5 % KOH, and then heated to temperature up to 750 °C for two hours. The residues were washed several times with distilled water to remove the acid from the residues and then dried in oven at 40 °C.

2.6. Determination of Physico-chemical Characteristics of the Plant-Derived Activated Carbon

2.6.1. Determination of Densities

The bulk density (ρ_n), apparent density (ρ_p), and real density (ρ_r) of the activated carbon were determined using Powder Characteristics Tester, mercury displacement, and GeoPyc 1330 Envelope Density Analyzer as described by Webb and Orr (1997), Rouquerol et al. (1994), and Buczek (1991).

2.6.2. Determination of Pore Volume

The pore volume of the activated carbon was calculated from ρ_p and ρ_r using the following equation (1):

$$\text{Pore volume} = \frac{1}{\text{Apparent density}} - \frac{1}{\text{Real density}} \quad (1)$$

2.6.3. Determination of Porosity

The porosity (ε_c) of the activated carbon that includes the volume of interparticle space and the volume present inside adsorbent particles was determined from the following equation (2):

$$\text{Porosity} = 1 - \frac{\text{Apparent density}}{\text{Real density}} \quad (2)$$

2.6.4. Determination of Surface Area

The surface area of the activated carbon sample was determined using the method described by Dada et al. (2022). The sample (0.5 g) was treated with 25 cm^3 of 0.05 M iodine solution and then centrifuged to obtained true solution. Two drops of starch indicator were added to 20 cm^3 of the sample solution and distilled water and then titrated with 0.1 M sodium thiosulphate solution.

2.6.5. Determination of pH

The pH value of the activated carbon derived from *Typha domingensis* was measured using digital pH meter in triplicate, and the average pH value was obtained.

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2.6.6. Determination of Electrical Conductivity

A digital conductivity meter was used for measurement of electrical conductivity of the activated carbon derived from *Typha domingensis*. The values were measured three times and the average value was obtained.

2.6.7. Determination of Moisture Content

The moisture content of the activated carbon sample was determined using the method of Miroslav and Vladimir (1999). An empty clean crucible was weighed using analytical weighing balance. Two grams of the activated carbon sample was weighed into the crucible (W_1). The crucible with the sampled was weighed (W_2) and then dried in an oven at 125 °C for 3 hours. After drying, the sample was weighed again (W_3), following equation (3).

$$\text{Moisture content (\%)} = \frac{W_2 - W_1}{W_3} \text{ x } 100 \quad (3)$$

Where; W_1 is weight of sample, W_2 is weight of sample with container, and W_3 weight of sample after drying.

2.6.8. Determination of Ash Content

The dried sample was weighed (W_1) and then transferred in crucible. The sample was ashed in a muffle furnace at 600 ºC for 60 minutes. The sample was allowed to cool in a desiccator and then weighed (W_1) using electronic weighing balance. The ash content was calculated using the following equation (4):

$$\text{Ash content (\%)} = \frac{W_2}{W_1} \text{ x } 100 \quad (4)$$

Where; W_1 is the initial weight of the sample, W_2 is the final weight of the sample

2.7. Fourier Transform Infrared (FTIR) Spectroscopic Analysis

The main functional groups in the plant biosorbent were determined by Fourier Transform Infrared (FTIR) spectroscopic technique. The peaks representing functional groups in the sample were detected using FTIR spectrophotometer (Agilent Technologies, Happ-Genzel) at a wave number ranged 650 – 4000 cm^{-1} and at 4 cm^{-1} resolution. The sample in drop was introduced between two plates of KBr cells. Formation of thin film in between the plates that enable the flow of light through the sample was observed. The plates were placed in the sample holder, positioned in the standard compartment and then spectra were generated.

2.8. Determination of Heavy Metals Content

The concentrations of cadmium, cobalt, manganese, lead, nickel, and chromium in the treated and untreated industrial wastewater sample were estimated by atomic absorption spectroscopic (AAS) technique using spectrophotometer (PerkinElmer PinAAcle 900H1) as described by AOAC (2005) and Abubakar et al. (2025). One mile of concentrated nitric acid and 2 g of anti-bump were added into the conical flask containing 100 mL of the wastewater sample. The solution was heated at 65 °C for 5 minutes, cooled and then filtered using Whatman filter paper. For calibration analysis, standard solutions (0.1 mg/L to 10 mg/L) were prepared from the diluted stock solution (1000 mg/L) of the metals. Specifically, de-ionized water and calibration standards for each metal were prepared. For each metal, the absorbance was measured at 450 nm wavelength. The concentration of each metal was obtained from the respective calibration curve.

2.9. Batch Adsorption Study

Batch adsorption study was carried out using the method of APHA (2018), Tichaona et al. (2013), and Dawodu et al. (2014). The concentration of different heavy metals present in the wastewater was determined using atomic absorption spectroscopic (AAS) technique. The industrial wastewater (500 mL) containing heavy metals and other pollutants was treated with 5 g of the activated carbon in a conical flask. The conical flask was corked and agitated in a magnetic stirrer for 60 minutes at 100 rpm speed and at room temperature. The contents were filtered to separate the activated carbon from the liquid phase. The final (equilibrium) concentration of the heavy metals in the supernatant was determined using AAS method. The amount of each heavy metal adsorbed was calculated based on the difference between the initial and final or equilibrium concentration of the metal, using the following equation (5):

$$q_e = \frac{C_o - C_e}{M} \text{ x } V \quad (5)$$

The heavy metal removal efficiency of the activated carbon was obtained using following equation (6):

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$$\text{Removal efficiency } (\%) = \frac{C_o - C_e}{C_o} \text{ x } 100 \quad (6)$$

Where; q_e is the amount of heavy metal adsorbed (mg/g) at equilibrium, C_o is the initial concentration of the heavy metal (mg/L), C_e is the equilibrium or final concentration (mg/L), M is the mass of the activated carbon (g), V is the volume of wastewater containing the metal ions (L)

2.10. Evaluation of Mechanism of Heavy Metals Adsorption Capacity of the Plant-Derived Activated Carbon

The mechanism of heavy metals adsorption capacity of the plant-derived activated carbon was evaluated using Freundlich isotherm and Langmuir isotherm models. The batch adsorption experimental data for each heavy metal were plotted on Langmuir isotherm and Freundlich isotherm equations. The linear Freundlich equation (7) is:

$$\log(q_e) = \log(K_F) + \frac{1}{n}\log(C_e) \quad (7)$$

Where; C_e is the equilibrium concentration of sorbate (mg/L), q_e is the amount of sorbate adsorbed at equilibrium (mg/g), K_F is Freundlich constant indicating adsorption capacity and n is Freundlich exponent indicating adsorption intensity.

From the experimental data, log q_e was plotted against log C_e generating a straight line graph of slope 1/n and intercept log K_F. The values of K_F, n, and R^2 for each metal were calculated and recorded.

The linear Langmuir equation (8) is:

$$\frac{C_e}{q_e} = \frac{1}{q_m K_L} + \frac{C_e}{q_m} \quad (8)$$

Where; C_e is the concentration of sorbate at equilibrium (mg/L), q_e is the amount of metal ions adsorbed at equilibrium (mg/g), q_m is the maximum amount of metal ions that can be adsorbed (mg/g), and K_L is Langmuir constant related to the energy of adsorption (L/mg) (Ho et al., 2005).

From the experimental data, C_e/q_e was plotted against C_e giving a straight line graph with a slope $1/q_m$ and intercept $1/K_L q_m$. The values of K_L, q_m, and R^2 for each metal were calculated and recorded.

2.11. Statistical Analysis

All the experiments were conducted in triplicate. The average values were obtained and the results were expressed as mean ± SEM. The significant differences between the means values were analyzed by one-way ANOVA using Dunnet multiple comparison test at 95 % confidence level. Two-tailed ($p < 0.05$) value was considered significance

3. Result and Discussion

In this study, potassium hydroxide activator method was used for the production of activated carbon from the roots sample of *Typha domingensis*. The advantages of potassium hydroxide activator over the other chemical activators include wide applications and production of activated carbon with a complex microporous structure and high pore size (Shi and Liu, 2021). The method has significant of producing biosorbent with higher carbon content, more specific porosity, and high adsorption capacity (Zubrik et al., 2017).

3.1. Physico-chemical Characteristics of the Plant-Derived Activated Carbon

Table 1 shows the physico-chemical characteristics of the activated carbon derived from the roots sample of *Typha domingensis*. The result showed that the activated carbon derived from *Typha* domingensis displayed high significant ($p < 0.05$) value of surface area (570.33 m^2/g), pore volume (2.56 g/cm^3), pH (6.46), conductivity (64.03 μS/cm), moisture content (20.86 %), and ash content (7.53 %) coupled with low value of porosity (0.82 %), bulk density (0.53 g/cm^3), apparent density (0.32 g/cm^3), and real density (1.91 g/cm^3) (Table 1).

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Table 1. Physico-chemical characteristics of the plant-derived activated carbon

Characteristic	Activated Carbon
Surface area (m^2/g)	570.33 ± 0.881
Porosity (%)	0.82 ± 0.001
Pore volume (g/cm^3)	2.56 ± 0.023
Bulk density (g/cm^3)	0.53 ± 0.002
Apparent density (g/cm^3)	0.32 ± 0.012
Real density (g/cm^3)	1.91 ± 0.023
pH	6.46 ± 0.233
Conductivity (μS/cm)	64.03 ± 0.260
Moisture content (%)	20.86 ± 0.318
Ash content (%)	7.53 ± 0.176

Results are expressed as mean ± SEM (n = 3)

Physico-chemical characteristics of activated carbon affect its adsorption capacity. They determine the amount and rate of pollutants adsorption by adsorbents. The adsorption performance of plant-derived activated carbon depends on the its surface characteristics including surface area, pore volume, pH, bulk density, and the presence of functional groups (Afroze et al., 2016; Dawood et al., 2014). In this study, the activated carbon derived from *Typha domingensis* exhibited high value of surface area, pore volume, pH, conductivity, moisture content, and ash content coupled with low values of porosity, bulk density, apparent density, and real density. The result of this study is in agreement with the finding of similar study which showed that activated carbon produced from Maize cob displayed higher value of surface area, pore volume, moisture and ash contents (Sanyaolu et al., 2022). Results of a relevant studies by Wasilewska et al. (2021) and Deryło-Marczewska et al. (2010) indicated that carbons from aqueous solutions exhibited high value of surface area and pore volume with a micropore content of about 40 – 46 %. High surface area is associated with the low particle density indicating high adsorption capacity of biosorbent (Abia & Igwe, 2005).

Surface area is one of the major factors that affect adsorption of pollutants by adsorbents. Surface area determines the degree or extent of adsorbing pollutants including heavy metals onto to the surface of adsorbents (Nguyen, et al., 2013). It has been documented that higher surface area of activated carbon is an important indicator of its high adsorption capacity (Nasar & Mashkoor, 2019). Bulk density is an important factor that affects the adsorption performance of plant-derived activated carbon. Activated carbon with low bulk density is characterized by high adsorption performance (Li et al., 2019; Shen et al., 2018; Safdari et al., 2018). High adsorption performance is associated with high pH value of adsorbent. The pH affects the adsorption capacity of adsorbent by changing the adsorbent surface charges, degree of ionisation, and metal speciation (Marwa et al., 2021; Kyzas et al., 2015). Study showed that the percentage removal of Pb^{2+} and Ni^{2+} was increased with the increase in the pH value (Cruz-Lopes et al., 2021). Larger pore volume of adsorbent or activated carbon is an important factor indicating its high adsorption performance. Larger pore volume of adsorbent indicates its high capacity for adsorbing more pollutants (Smith & Carter, 2023). The larger the pore volume of adsorbent or activated carbon the high its adsorption capacity and the more pollutants it adsorb (Hassan & Carr, 2021; Moosavi et al., 2020).

3.2. FT–IR Analysis of the Plant-Derived Activated Carbon

Figure 1 shows the FT-IR spectrum of the activated carbon derived from the roots sample of *Typha domingensis*. The spectrum displayed various peaks at different wavenumber ranged 3350 – 801 cm^{-1} with bands indicating different functional groups present in the plant-derived activated carbon (Figure 1).

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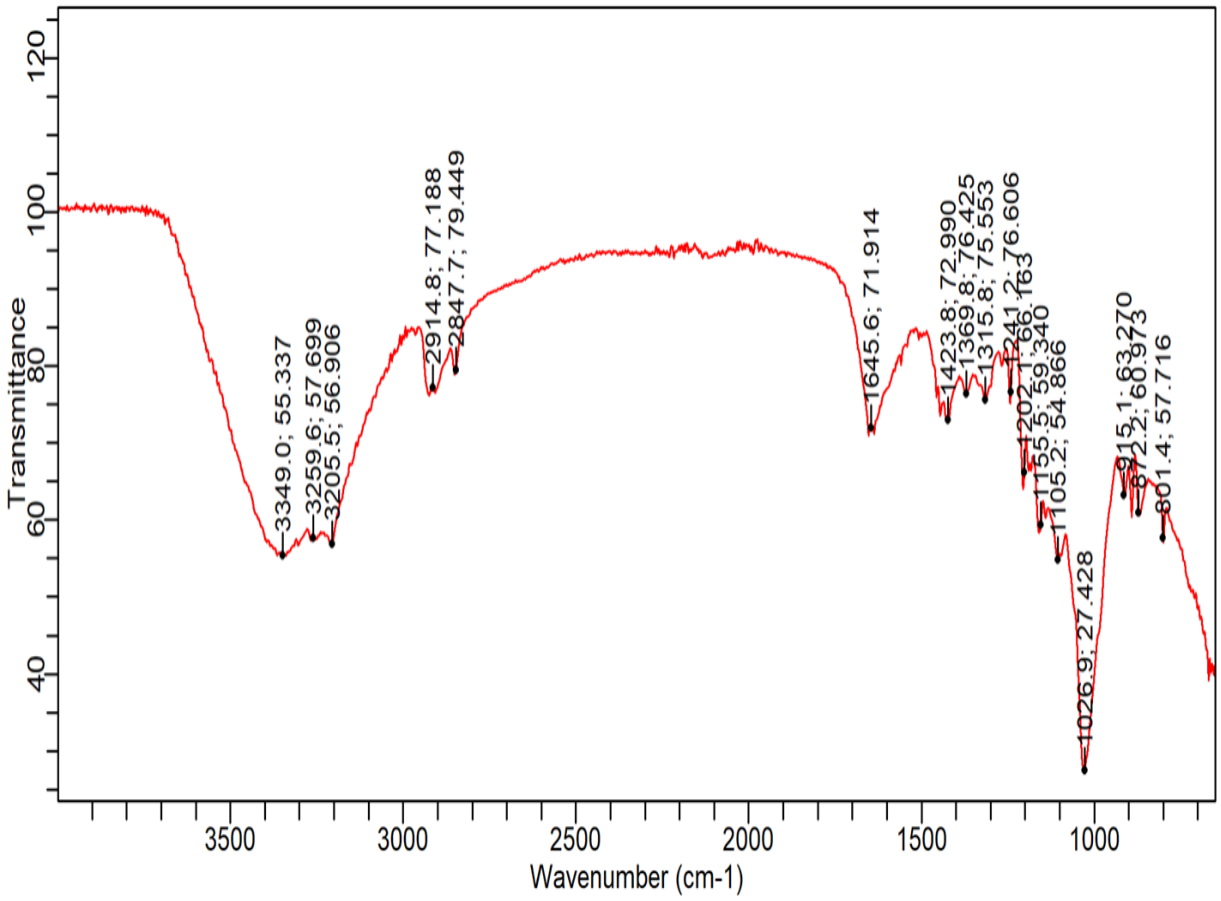


Figure 1. FT-IR spectrum of the plant-derived activated carbon

The functional groups present in the plant-derived activated carbon with specific absorption intensity are presented in Table 2. The FT-IR spectrum of the activated carbon displayed maximum peaks at 2847.7 cm^{-1} (79.45 %), 2914.8 cm^{-1} (77.19 %), 1241.2 cm^{-1} (76.61 %), 1369.8 cm^{-1} (76.43 %), 1315.8 cm^{-1} (75.55 %), 1423.8 cm^{-1} (72.99 %), and 1645.6 cm^{-1} (71.91 %). The band peaks observed at 2847.7 cm^{-1} and 2914.8 cm^{-1} indicated strong C–H stretching. The band peak showing strong stretching of C=O was detected at 1645.6 cm^{-1}. A strong C–C stretching was found on the band peaks at 1369.8 cm^{-1}, 1315.8 cm^{-1}, and 1423.8 cm^{-1}. However, strong vibration of C–O was observed on the band peak detected at 1241.2 cm^{-1}. The spectrum showed a medium peaks (66.16 %, 63.27 %, 60.97 %, 59.34 %, 57.72 %, 57.69 %, 56.91 %, 55.34 %, 54.87 %) at 1202.1 cm^{-1}, 915.1 cm^{-1}, 872.2 cm^{-1}, 1155.5 cm^{-1}, 801.4 cm^{-1}, 3259.6 cm^{-1}, 3205.5 cm^{-1}, 3349.0 cm^{-1}, and 1105.2 cm^{-1}, respectively. The band peaks observed at 915.1 cm^{-1}, 872.2 cm^{-1}, and 801.4 cm^{-1} could likely be due to medium vibration of C=C. A medium O–H stretching was observed on the band peaks at 3259.6 cm^{-1}, 3205.5 cm^{-1}, and 3349.0 cm^{-1}. However, a weak stretching of C–O was found on the band peaks detected at 1026.9 cm^{-1} (Table 2).

Table 2. Functional groups present in the plant-derived activated carbon

Absorption (cm^{-1})	Transmittance (%)	Intensity	Functional Group
3350 – 3206	55 – 58	Medium	O–H
2915 – 2848	77 – 80	Strong	C–H
1750 – 1645	70 – 72	Strong	C=O
1425 – 1315	72 – 77	Strong	C–C
1242 – 1026	27 – 77	Strong, Medium, Weak	C–O
916 – 801	57 – 64	Medium	C=C

Data are presented as mean ± SEM (n = 3)

In this study, FT-IR spectrum of the activated carbon displayed various band peaks at wavenumber ranged 3350 – 801 cm^{-1} indicating stretching of C–H, C=O, C–C C–O, and O–H. Similar study showed that FT-IR spectrum of a plant

sample displayed broad band peaks at 3328 cm^{-1} and 2938 cm^{-1} indicating N-H,O-H stretching vibration and aliphatic C-H stretching vibrations of -CH3 and -CH2 functional groups (Azubuike & Okhamafe, 2012). It has been reported that peaks at about 1067 cm^{-1} indicate strong C–O stretching, and the peaks between 1250 and 1400 cm^{-1} indicate strong vibrations of CH_2 and CH_3 (Choi, 2017). The vibration peak at around 1670 cm^{-1} and 2917 cm^{-1} shows C=O stretching and C–H stretching, respectively. Relevant study indicated that broad and strong bands at around 3392 cm^{-1} indicate O–H stretching (Lee & Choi, 2018). In this study, the difference in absorption intensity and the wavenumber of the functional groups could be attributed to nature of interaction between metal ions and binding sites of the bio-sorbent indicating significant bio-sorption of the metal ions on the bio-sorbent.

Different functional groups found on the surfaces of biosorbents include alkyl halides (R-I), alkenes (=C-H), aromatic compound mono substituted (C-H), alcohols (C-O), alkyl halides (C-F), ethers (=C-O-C), alkanes and alkyls (C-H), aromatic compounds (C=C), amides (N-H), alkenes (C=C), aldehydes (C=O), esters (C=O), carboxylic acids (O-H) (Dawodu & Akpomie, 2014). These functional groups have ability to bind metal ions and molecules and have involved in the biosorption of the heavy metals (Huang & Zhu, 2013). The presence of functional groups on the surface of plant-derived activated carbon determines the hydrophobicity or hydrophilicity of pollutants and their adsorptive mechanism (Law et al., 2022). Study showed that carboxyl and hydroxyl groups found on the surface of sorghum biomass played a significant role in the removal of Pb (II) from an aqueous solution (Salman et al. 2014). It was also reported that hydroxyl, amine, carboxyl, and carbonyl groups were responsible for the adsorption of Ni (II) onto Caesalpinia bonducella seed powder (Gutha et al. 2011). Studies revealed the effective interaction of carboxyl and hydroxyl groups towards heavy metal ions (Vieira et al. 2012, Araújo et al. 2010, Martín-Lara et al. 2013).

3.3 Heavy Metals Content of the Wastewater

The concentrations of cadmium, cobalt, lead, manganese, nickel, and chromium in the industrial wastewater sample are presented in Figure 2. High significant ($p < 0.05$) amount of cadmium (0.23 mg/L), cobalt (0.83 mg/L), lead (3.02 mg/L), manganese (1.47 mg/L), nickel (0.62 mg/L), and chromium (0.60 mg/L) was found in the wastewater sample (Figure 2).

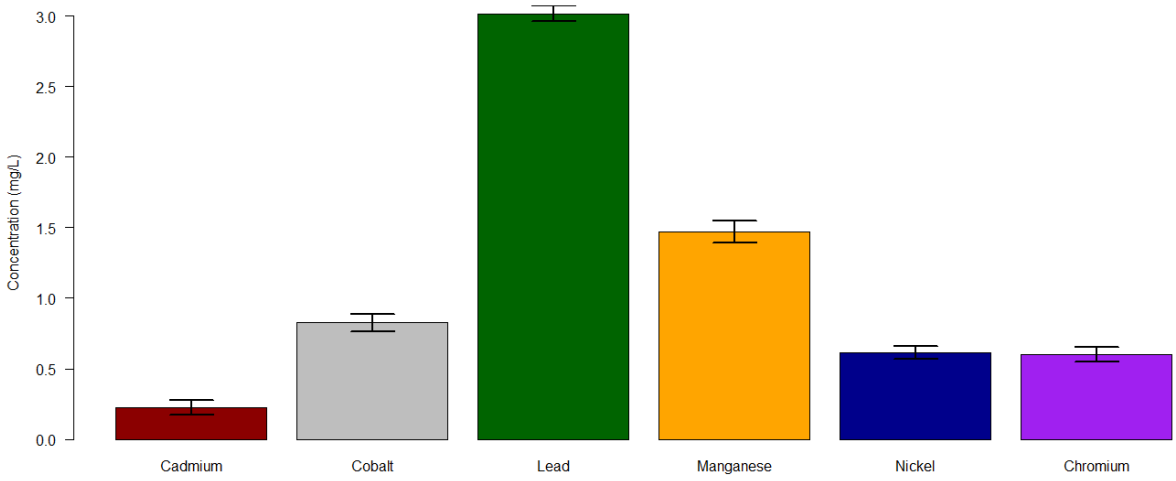


Figure 2. Heavy metals content of the wastewater

Values are given as mean ± SEM (n = 3)

In the present study, high concentration of cadmium, cobalt, lead, manganese, nickel, and chromium was found in the industrial wastewater sample. Consumption of heavy metals causes toxic effect on many organs and tissues including damage of nervous system, influencing fetal development, carcinogenicity and impaired immune function (Abubakar et al., 2025; Abubakar et al., 2022).

3.4 Heavy Metals Removal Efficiency of the Plant-Derived Activated Carbon

Figure 3 shows the percentage efficiency of the activated carbon derived from the roots of *Typha domingensis* for removal of cadmium, cobalt, lead, manganese, nickel, and chromium from the industrial wastewater sample. The

activated carbon exhibited high percentage efficiency for removal of cadmium (95.55 %), cobalt (96.48 %), lead (97.16 %), manganese (99.25 %), nickel (96.09 %), and chromium (96.88 %) from the wastewater sample (Figure 3).

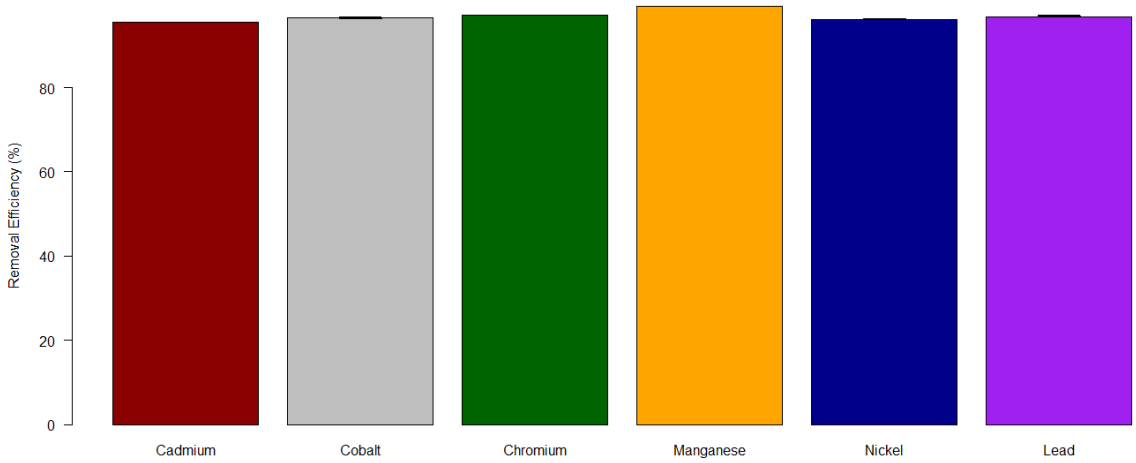


Figure 3. Heavy metals removal efficiency of the plant-derived activated carbon
Results are expressed as mean ± SEM (n = 3).

In this study, the activated carbon derived from the roots of *Typha domingensis* demonstrated high efficiency for removal of cadmium, cobalt, lead, manganese, nickel, and chromium from the industrial wastewater. The result of this study agrees with the finding of similar studies that revealed that *Typha domingensis* exhibited high removal efficiency of heavy metals including As, Co, Cu, Ni, Pb, Zn and Hg with bioaccumulation factors between 7 and 3618 (Compaore et al., 2020; Lominchar et al., 2015). The present finding was in line with the findings of similar studies by Dube et al. (2019) and Hadad et al. (2018) who reported that *Typha domingensis* has significant capacity stabilizing heavy metals such as Cr, Ni, Zn, Fe, Cd and Cr in polluted aquatic environments. However, similar finding revealed that Typha species demonstrated high accumulation of Al (1890 mg/kg), As (2.86 mg/kg), Cr (18.5 mg/ kg), Pb (13.7 mg/kg), and Zn (122 mg/kg) in natural wetland indicating their significant phytoremediation efficiency (Bonanno et al., 2017). Similar study showed that Typha latifolia which belongs to the same genus with *Typha domingensis* exhibited significant pollutants removal efficiency from wastewater (Amit et al., 2021). In another relevant studies, Typha latifolia displayed high efficiency for removal of Fe, Cu, Zn, Pb and Ni from the mining effluents Riverine wetlands (Nabuyanda et al., 2022; Milke et al., 2020).

3.5 Mechanism of Heavy Metals Adsorption Capacity of the Plant-Derived Activated Carbon

The plots of the Freundlich isotherm model for adsorption of cadmium, cobalt, lead, manganese, nickel, and chromium from the industrial wastewater sample by the activated carbon derived from the roots of *Typha domingensis* is shown in Figure 4.

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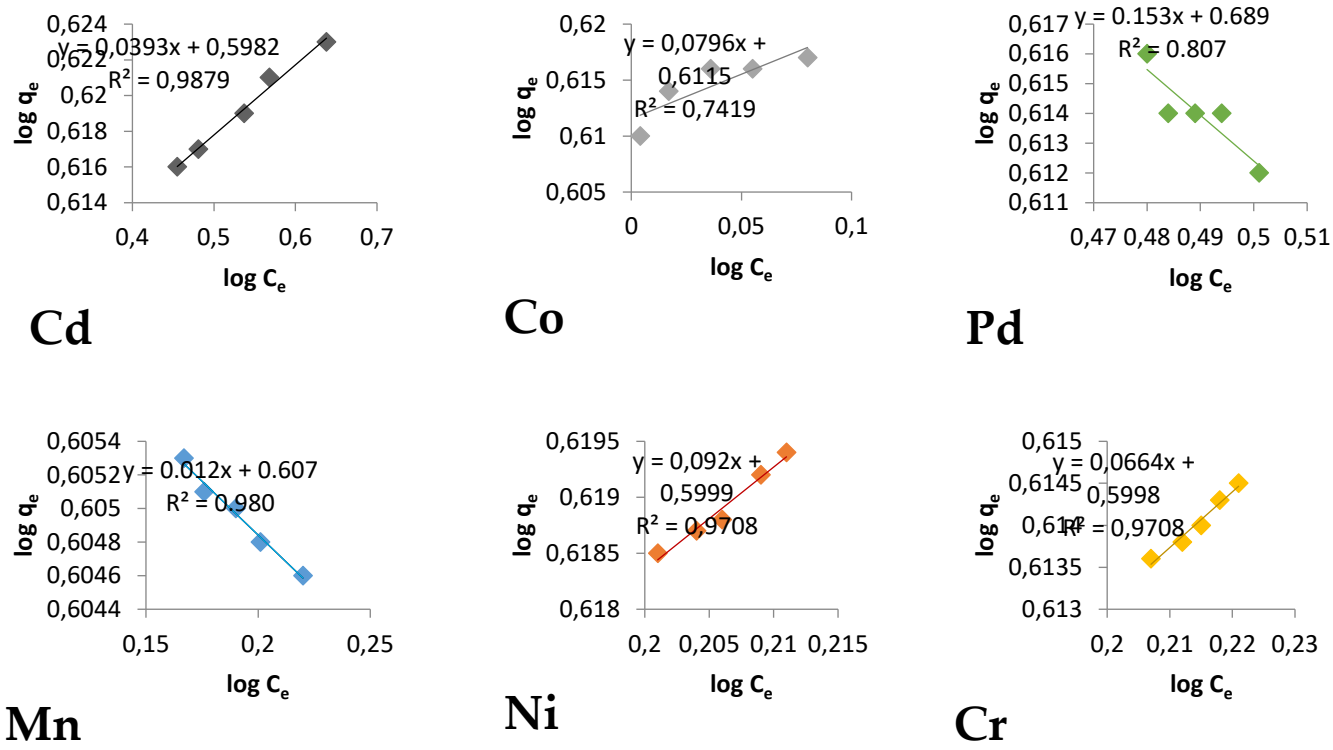


Figure 4. Freundlich isotherm model for adsorption of heavy metals

Figure 5 shows the plots of Langmuir isotherm model for adsorption of cadmium, cobalt, lead, manganese, nickel, and chromium from the industrial wastewater sample by the activated carbon derived from the roots of *Typha domingensis*.

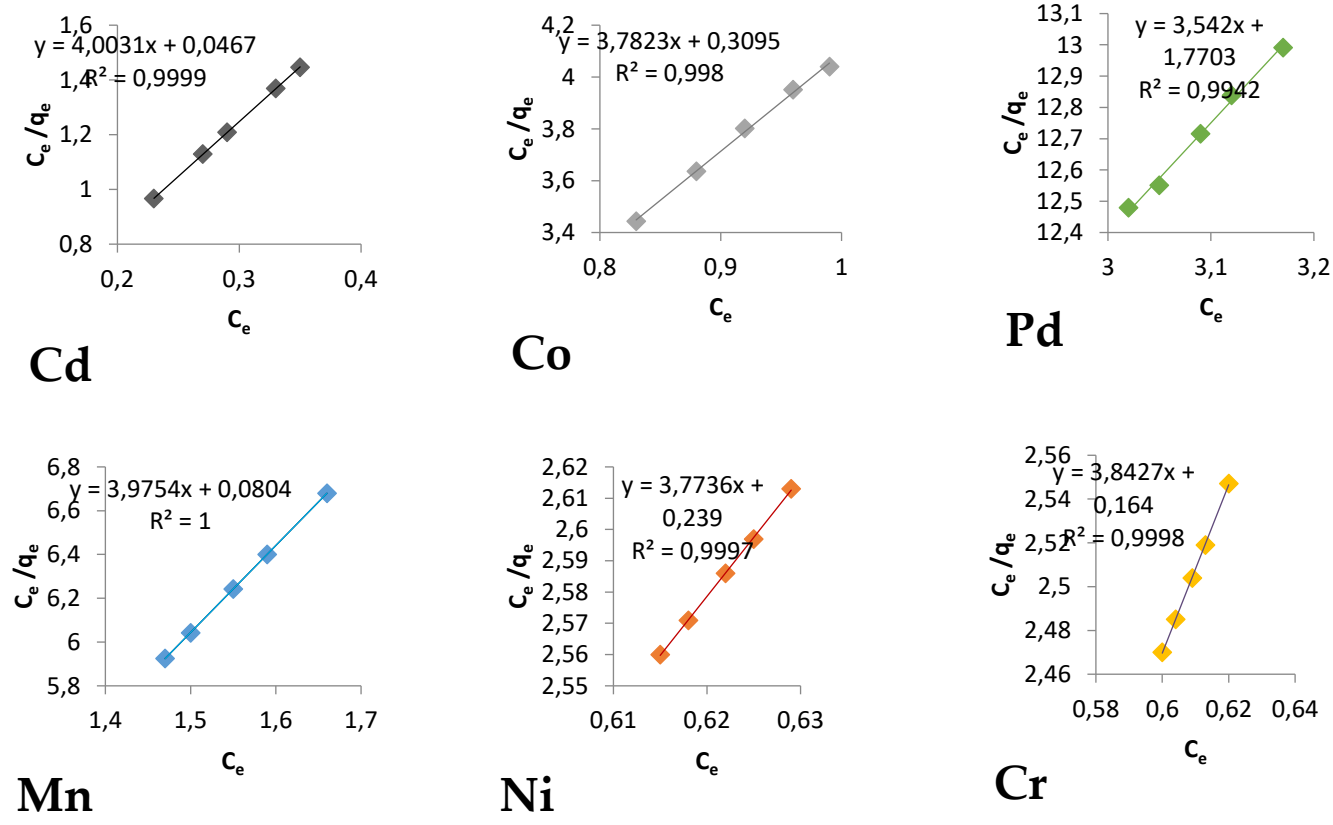


Figure 5. Langmuir isotherm model for adsorption of heavy metals

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Table 3 shows the Freundlich and Langmuir isotherms constant parameters for the adsorption of cadmium, cobalt, lead, manganese, nickel, and chromium from the industrial wastewater sample by the activated carbon derived from the roots of *Typha domingensis*. From the Freundlich isotherm plots, manganese displayed higher Freundlich constant (n) value (83.333) than the other analyzed metals. Higher significant adsorption capacity (K_F) value was observed for all the metals with lead (4.886) being the highest. From the Langmuir isotherm plots, lead and cadmium demonstrated high value of monolayer adsorption capacity (q_m) (0.282) and Langmuir constant (K_L) (90.90), respectively. The regression coefficient (R^2) values of all the metals for the Langmuir isotherm model are higher than that exhibited by the metals for the Freundlich isotherm model (Table 3).

Table 3. Freundlich and langmuir isotherm constant parameters for adsorption of heavy metals

Heavy Metal	Freundlich Isotherm			Langmuir Isotherm		
	n	K_F	R^2	q_m	K_L	R^2
Cadmium	25.640	3.962	0.987	0.249	90.90	0.999
Cobalt	12.658	4.083	0.741	0.264	12.345	0.998
Lead	6.535	4.886	0.807	0.282	2.004	0.994
Manganese	83.333	4.045	0.980	0.251	50.000	1.000
Nickel	10.869	3.971	0.970	0.265	15.873	0.999
Chromium	15.151	3.971	0.970	0.260	23.809	0.999

In this study, the Langmuir and Freundlich isotherm models were used to evaluate the mechanism of heavy metals adsorption by the activated carbon derived from *Typha domingensis*. Adsorption isotherm models describe the equilibrium relationship between the sorbate (metal ion) in the fluid phase (solution) and the sorbate adsorbed on the sorbent (adsorbent) at constant temperature (Binupriya et al., 2009). Biosorption isotherm models have been used to evaluate the efficiency of biosorbents for removal of heavy metals and organic pollutants from polluted substances (Khatoon & Rai, 2016). The results of this study showed that the regression coefficient (R^2) values of cadmium, cobalt, lead, manganese, nickel, and chromium for the Langmuir isotherm are higher than that demonstrated by the metals for the Freundlich isotherm model. Thus, the experimental equilibrium data for cadmium, cobalt, lead, manganese, nickel, and chromium were best fitted to the Langmuir isotherm model than the Freundlich isotherm model. This finding is in line with the result of similar study by Uddin et al. (2007) who found that adsorption of phenol by water hyacinth was best fitted to Langmuir isotherm model than the Freundlich isotherm model. Relevant research by Lalhruaitluanga et al. (2010) revealed that the adsorption of lead ions in solution by the activated charcoals derived from *Melocanna baccifera* Roxburgh was best fitted to Langmuir isotherm model. Also study by Nwabanne and Igbokwe (2008) showed that data for adsorption of nickel ion by cassava peels were best fitted to Langmuir isotherm with X_m value up to 4.74. The present finding is also in agreement with the finding of similar study which showed that the experimental data for adsorption of lead and cadmium by biosorbents derived from dragon fruit peel, rambutan peel, and passion fruit peel were best fitted to the Langmuir model (Wattanakornsiri et al., 2022).

The values of Langmuir isotherm constant parameters provide significant information on the adsorbate-adsorbent relationships, surface properties, and adsorption mechanism (Kumar, 2006). The Langmuir isotherm constant values are used to indicate the maximum adsorption capacity of biosorbent that could not be evaluated experimentally. The value of K_L is a major criterion in selecting a biosorbent for wastewater treatment (Ho et al., 2005). The K_L value indicates the interaction affinity between adsorbate and adsorbent molecules (Tran et al., 2017). Low K_L value implies low surface energy in the adsorption process and low bonding between metal ions and biosorbent indicating a physisorption mechanism (Huang & Zhu, 2013). Langmuir isotherm model is based on the assumption that the surface adsorption mechanism displays as a monolayer onto the adsorbent material and indicates distribution of adsorbate between solid and liquid layers at equilibrium (Fakhry et al., 2022). Langmuir isotherm model implies a monolayer adsorption mechanism with homogeneous adsorption energy (Tung et al., 2022). Hence, the *Typha domingensis* derived activated carbon adsorbed cadmium, cobalt, lead, manganese, nickel, and chromium from the industrial wastewater on a single surface layer with homogeneous adsorption energy.

4. Conclusion

The WACOT rice industrial wastewater contains significant amount of cadmium, cobalt, lead, manganese, nickel, and chromium. The activated carbon derived from the roots of *Typha domingensis* demonstrated high adsorption capacity for removal of cadmium, cobalt, lead, manganese, nickel, and chromium from the industrial wastewater. The

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experimental equilibrium data for cadmium, cobalt, lead, manganese, nickel, and chromium were best fitted to the Langmuir isotherm model.

Conflict of Interest

The authors declared no conflict of interest.

Provide your final conclusion here. In the conclusion section, it is not allowed to repeat all the data from the result section. Only the final findings and final conclusion only. Don't use any number or bulleting in the conclusion, only use paragraphs.

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