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Sustainable Adsorbents: Characterisation of Banana Stem-Based Materials for Reactive Black 5 Dye Removal

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Abstract

Banana stems are agricultural plant waste from one of Asia's most popular fruits, which is grown primarily in India, Thailand, China, Indonesia, and Malaysia. Since coal-derived activated carbon is expensive and has limited availability, agricultural waste such as banana stems has been seen as an affordable and abundant alternative. Activated carbon banana stem (ACBS) was prepared by soaking with phosphoric acid (H_3PO_4) and heating in a furnace at 400°C for 1 hour. Both raw banana stem (RBS) and activated carbon banana stem (ACBS) were characterized using proximate analysis, Scanning Electron Microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR) and Brunauer–Emmett–Teller (BET). The results showed that ACBS had higher ash (25.45%) and fixed carbon (36.4%) contents, and lower moisture (2.3%) and volatile matter (35.85%) contents than RBS. Analysis of the surface morphology using SEM indicated that the ACBS was more porous than the RBS, thereby enhancing its adsorption capacity. BET analysis revealed that the surface area, pore volume, and average pore diameter of the ACBS (475.7 m^2/g, 0.4491cm3/g, and 3.776 nm) were significantly greater than those of the RBS (1.886 m^2/g, 0.0047 cm^3/g, and 9.882 nm), demonstrating effective pore development during activation. The results showed that ACBS was more effective at removing Reactive Black 5 (RB5) dye, with a removal efficiency of 99.11%, compared to RBS, which had only 6.4%.

1. Introduction

The dye industry is especially important to the manufacturing sector because it produces colours for many products, including paints, textiles, and plastics. Each year, approximately 7^7 tons of synthetic dyes are produced worldwide, with over 10,000 tons employed by the textile sector [1]. Dyes are typically classified into many groups based on their origin, structure, and application. Approximately 15% of dye is released into the environment as waste after dyeing [2]. Among widely used dyes, Reactive Black 5 (RB5) is particularly prominent for its high stability, complex aromatic structure, and widespread use in the textile industry [3]. Reactive Black 5 dye is classified as an industrial dye. The C.I. (Colour Index) number is 20505, which is classified as anionic, diazo [4]. This dye's negative charge not only makes it water-soluble but also enables it to interact with fibres, promoting bonding during dyeing. It is also very soluble in aqueous solutions and black in colour. This dye can block sunlight when released directly into lakes and rivers, disrupting aquatic ecosystems and endangering marine life. Before being safely released into the environment, wastewater contaminated with dyes is treated using a variety of techniques, including physical, chemical, and biological approaches, or combinations thereof [2]. Other techniques for dye removal from wastewater included ion exchange [5], biodegradation [6], oxidation [7], membrane process [8], adsorption [9], and solvent extraction [10. Among these, the adsorption process has been found to be more effective due to its simple design, high removal efficiency, and ease of operation [11]. This process has many uses, including water and air purification, gas purification, chromatography, and catalysis.

Activated carbon is highly effective in adsorption processes due to its high carbon content, low ash content, and well-developed porosity [12]. It is commonly used for carbon dioxide capture due to its excellent thermal stability at high temperatures, high adsorption capacity at ambient pressure, low acid-base reactivity, tunable surface chemistry, and high stability in moist conditions [13]. The surface of the activated carbon also contains functional groups that influence the solution pH and, consequently, the adsorption process [12]. These properties make it a useful material in a variety of industrial sectors. The production of activated carbon involves carbonising the samples, followed by physical or chemical activation to create a porous surface for adsorption [14]. In chemical activation, the samples are impregnated with activating agents such as zinc chloride ($ZnCl_2$), phosphoric acid (H_3PO_4) and potassium hydroxide (KOH) [15]. This technique greatly increases the surface area of activated carbon while also promoting the formation of pore structure.

Phosphoric acid is frequently preferred over other acids for activation processes because of its ability to precisely modify material properties while causing minimal damage. Compared to sulfuric or nitric acids, which can cause harmful oxidation reactions and the formation of byproducts such as sulfur oxides or nitrogen oxides, phosphoric acid ensures a more stable activation [16]. This stability favours the occurrence of micropores and mesopores, which increase surface area and porosity while retaining the material's structure. Furthermore, phosphoric acid leaves phosphate groups on the surface, which is useful for applications such as catalysis and adsorption [17]. Despite the benefits of activated carbon as an adsorbent, its high cost has recently led researchers to seek alternatives. To address this issue, researchers are currently focusing more on the use of agricultural waste as adsorbent media. Previous research indicates that adsorbents have been effectively synthesised from raw materials, including sawdust, rice husk, jujube seeds, maize cobs, durian peel, coconut shells, watermelon, wood, palm shells, tobacco stems, bean husks, hazelnut shells, mangosteen shells, banana peels, walnut shells [18] and citrus peel [19]. Activated carbon's effectiveness and adsorption capacity were influenced by the structure of raw agricultural waste, including its preparation methods.

In Malaysia, banana stems are one of the most abundant agricultural wastes. It contains lignocellulosic [20], which is suitable for the production of activated carbon. Banana stems also have strong mechanical properties and outstanding structural integrity because they are composed of 48.0% cellulose, 21.1% hemicellulose, and 15.7% lignin [21]. Its high porosity, moisture absorption capacity, and lightweight structure can enhance adsorption capacity when activated [22]. Studies have shown that activated carbon made from banana stems can efficiently adsorb organic dyes and heavy metals due to its advantageous surface chemistry and functional groups formed during activation [23]. Furthermore, the use of activated carbon derived from banana stems aligns with the United Nations Sustainable Development Goal (SDG) 6: Clean Water and Sanitation, which aims to improve water quality by reducing pollution and minimising the release of hazardous substances. This approach also supports SDG 12: Responsible Consumption and Production by promoting the economic use of agricultural waste, encouraging circular economy practices, and reducing environmental impact. This approach, which combines waste utilisation and water purification, helps to control pollution while also promoting sustainable resource management and environmental protection.

The objective of this study was to examine the effectiveness of banana stem powder and banana stem activated carbon as adsorbents and to characterise their physicochemical properties in terms of surface morphology, surface area, and compositional differences among functional groups. These capabilities are critical for optimising the performance of activated carbon in industrial applications such as adsorption and wastewater treatment.

2. Methodology

2.1 Preparation of Raw and Activated Banana Stems

The raw and activated banana stems were prepared according to Misran et al. [20], with some modifications, as shown in Fig. 1. The banana stems were cut into small pieces, cleaned with distilled water to remove impurities, and dried for 24 hours at 105˚C in an oven. To create a fine powder, the dried stems were ground and sieved to 0.5 μm using a grinder and sieve. To prepare ACBS, 1.0 M phosphoric acid (1:3 ratio) was mixed with powdered banana stems for 24 hours. Afterwards, the mixture was heated for 1 hour at 400 °C in a furnace. The resulting activated carbon was washed until its pH was neutral and then dried at 105 °C for 24 hours. Both activated carbon and raw powdered banana stem were stored in airtight bags.

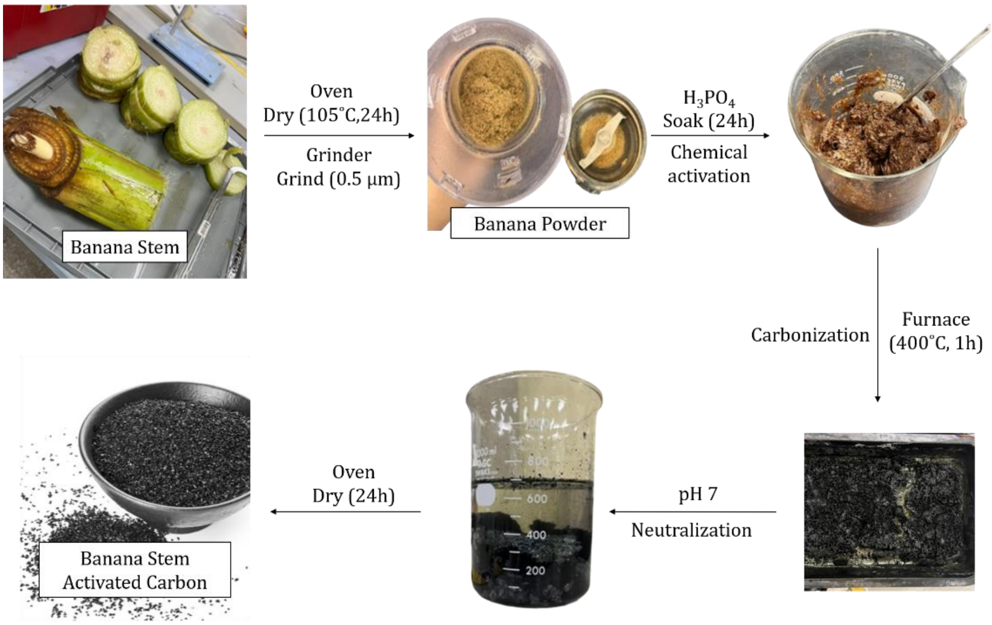


Fig. 1 *Sample preparation of banana powder (raw) and activated carbon from banana stem*

2.2 Characterisation of Raw and Activated Banana Stems

Both samples were characterized using Scanning Electron Microscopy (SEM) to examine the surface morphology while organic functional groups were analyzed using Fourier transform infrared spectroscopy (FTIR) and the BET (Brunauer-Emmett-Teller) surface area was examined using BET surface analyzer (Quantachrome Instruments) through the adsorption/desorption isotherms of N2 conducted at 77 K. A precise analysis was carried out to determine the distribution of moisture, ash, volatile matter and fixed carbon in the sample according to Fito et al. [24].

2.3 Removal of Reactive Black 5 Dye

In a 250 mL conical flask, 100 mL of Reactive Black 5 solution with an initial concentration of 200 ppm was mixed with 0.6 g of raw and activated banana stems. For two hours at room temperature, the mixture was shaken at 100 rpm. A UV–VIS spectrophotometer was then used to measure the final concentration of RB5 dye at a wavelength of 597 nm, as described in [25]. Each experiment is duplicated under similar conditions. The percentage of dye removal and adsorption capacity is calculated using Eqn. (1) and Eqn. (2).

$$\%\ Dye\ Removal = \frac{(C_0 - C_t)}{C_o} \text{ x } 100\% \quad (1)$$

$$Adsorption\ Capacity = \frac{(C_0 - C_t)\ V}{m} \quad (2)$$

where C_o is the dye solution's initial concentration (mg/L), C_t is the concentration of the dye solution at a certain contact time, *t*, *V* is the solution volume (L), and *m* is the adsorbent weight (g).

3. Results and Discussion

3.1 Proximate Analysis of Raw and Activated Banana Stems

Proximate analysis presents the physicochemical properties of the samples, specifically moisture, ash, volatile matter, and fixed carbon. These factors are critical in determining if a material is suitable as a precursor for activated carbon production. Table 1 shows the proximate analyses of RBS and ACBS. The results show a significant change in chemical composition between RBS and ACBS due to the activation process. The moisture content of RBS (8.67%) is higher than that of ACBS (2.3%) because it has not undergone thermal treatment, which would otherwise remove bound and free water [26], thereby improving stability and adsorption capacity. RBS was also higher in volatile matter content (67.11%) than ACBS (35.85%). The decrease in the result of the RBS to ACBS caused by the breakdown of hemicellulose, cellulose, and lignin, which improves the thermal stability and adsorption efficiency of the material [27].

ACBS has a relatively high ash content of 25.45%, whereas RBS has 18.54%, likely due to carbon enrichment [26]. Although the high ash content reduces the adsorption efficiency, it also enhances the structural integrity of activated carbon [27]. The high carbon content of ACBS (36.4%) directly contributes to porosity and adsorption capacity, meeting the activated carbon requirement stated in [28]. These findings suggested that the activation process effectively increases the carbon content, making ACBS suitable for adsorption applications, particularly for dye and heavy metal removal, and for use as a renewable precursor in energy-related applications.

Table 1 *Proximate analysis of RBS and ACBS*

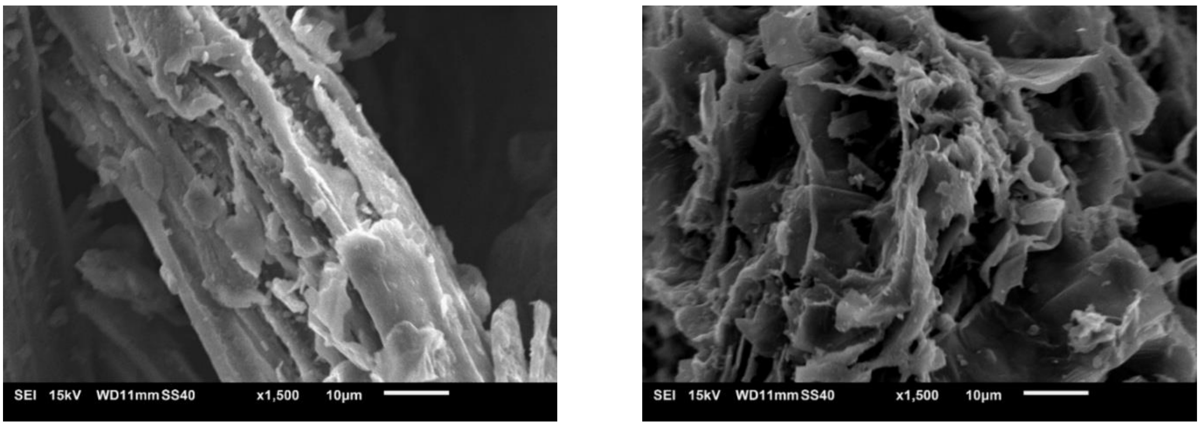
	Moisture Content (%)	Volatile Matter Content (%)	Ash Content (%)	Fixed Carbon Content (%)
RBS	8.67	67.11	18.54	5.68
ACBS	2.3	35.85	25.45	36.4

3.2 Surface Morphology of Raw and Activated Banana Stems

The study of surface morphology using SEM is essential for understanding the adsorbent's physical structure. Morphological parameters such as surface roughness, pore formation, and particle dispersion are all closely related to the material's adsorption effectiveness. Fig. 2 shows the differences between SEM photographs of raw and activated banana stem carbon obtained at 1500× magnifications due to the activation process with H_3PO_4. For the RBS, the structure is compact and exhibits lower porosity, resulting in a low surface area and limited adsorption capacity. Cell walls remain dense, restricting the formation of active sites for adsorption [29].

However, after chemical activation, both the surface morphology and porosity have changed. It shows a rough, porous structure in ACBS that is significantly different from the RBS. This increase in porosity directly increases surface area and pore volume, which can improve efficiency in adsorption applications [29].

Comparable morphological alterations have been documented in activated carbons derived from banana stems following chemical activation [20], indicating that phosphoric acid is an effective activating agent for the formation of porous structures. These findings confirm that the activation process not only increases carbon content, as indicated by the proximate analysis in Table 1, but also significantly modifies the physical structure, thereby enhancing the potential of ACBS for adsorption applications such as dye and heavy metal removal.



(a) (b)

Fig. 2 *Scanning electron micrographs of (a) RBS; (b) ACBS*

3.3 Organic Functional Groups of Raw and Activated Banana Stems

The FTIR technique was utilised to investigate the surface functional groups of the adsorbent. These functional groups are essential because they influence how the adsorbent and dye molecules interact and reveal details about the adsorption process. Fig. 3 and Table 2 show the functional groups identified by FTIR analysis of RBS and ACBS. RBS displayed peaks corresponding to -OH (3413 cm^{-1}) that are present in the structure of lignin, cellulose and hemicellulose [26], C-H (2924 cm^{-1}), C=O (1639 cm^{-1}), and C-O (1056 cm^{-1}).

The activation process altered the ACBS peaks. The -OH peak (3430 cm^{-1}) decreased due to the removal of adsorbed water in the raw material and degradation of the initial compound [26]. The C=O peak (1625 cm^{-1}) became more visible as the number of oxygen- containing functional groups increased [30]. Activation increased the carbonisation and graphitisation of the C-O peaks (1249 cm^{-1}) and aromatic peaks (617 cm^{-1}), thereby improving the material's adsorption capacity [31]. The successful conversion of RBS into ACBS improves its adsorption properties, making it useful for water purification, gas adsorption, and energy storage [31].

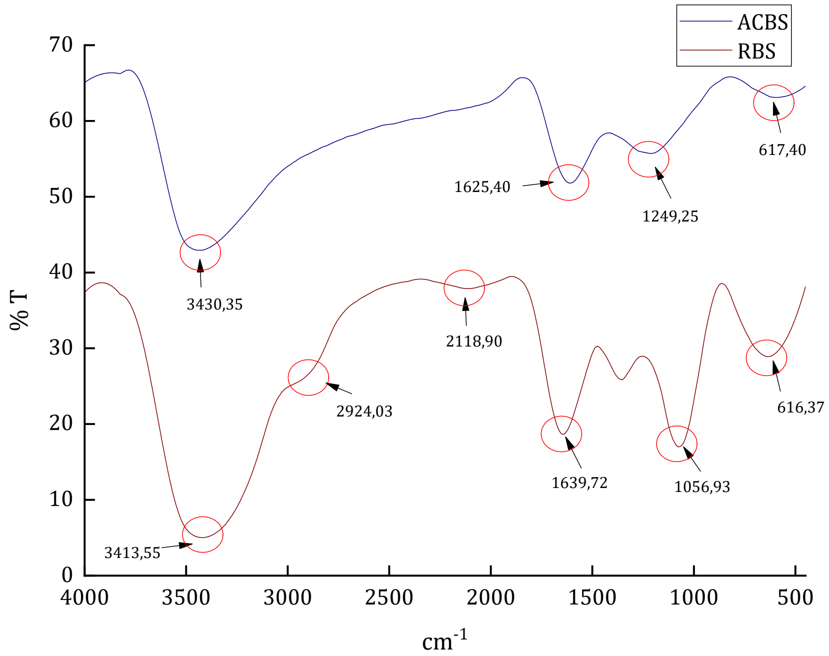


Fig. 3 *Fourier-transform infrared spectroscopy of RBS and ACBS*

Table 2 *Main characteristic band of RBS and ACBS*

Wavenumber (cm^{-1})	RBS	ACBS	Vibrational Bands
3413-3430	3413	3430	O–H stretching (hydroxyl groups)
2924	2924	-	C–H stretching (aliphatic CH_2/CH_3)
1625-1639	1639	1625	C=O stretching (carbonyl groups)
1249	-	1249	C-O stretching (carbohydrate/alcohols)
616-617	616	617	C–H out-of-plane bending (aromatic structures)

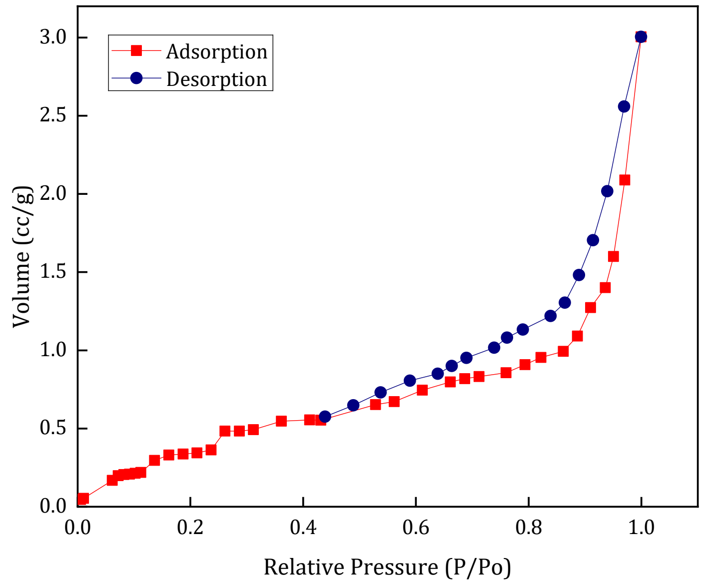
3.4 Surface Area and Pore Characterisation

The BET technique was employed to analyse the surface area and porosity characteristics of the raw and activated samples. Since adsorption largely depends on surface area and pore structure, this analysis provides valuable insight into the effectiveness of the activation process. The BET measurement results (see Table 3) show a significant improvement in the textural properties of ACBS compared with those of raw banana stem (RBS) powder. In ACBS, the specific surface area increased from 1.89 m^2/g in RBS powder to 475.7 m^2/g. Furthermore, the total pore volume increased from 0.0047 cm^3/g to 0.4491 cm^3/g. This remarkable improvement indicates that the activation and pyrolysis processes were highly effective in increasing porosity [32], as demonstrated by the SEM images in Fig. 2. The treatments removed ash and inorganic impurities that had previously blocked the pores of RBS, releasing and enlarging the accessible surface of ACBS. Pyrolysis increased pore generation by releasing volatile components, resulting in a well-developed porous matrix. Next, the pore diameter measures 9.882 nm for RBS powder and 3.776 nm for ACBS. The reduction in pore diameter corresponds with the increase in surface area of the ACBS after the activation and pyrolysis processes [32]. Also, the breakdown of aliphatic functional groups, as demonstrated by FTIR analysis in this study, contributed to the increased surface area and pore volume [33].

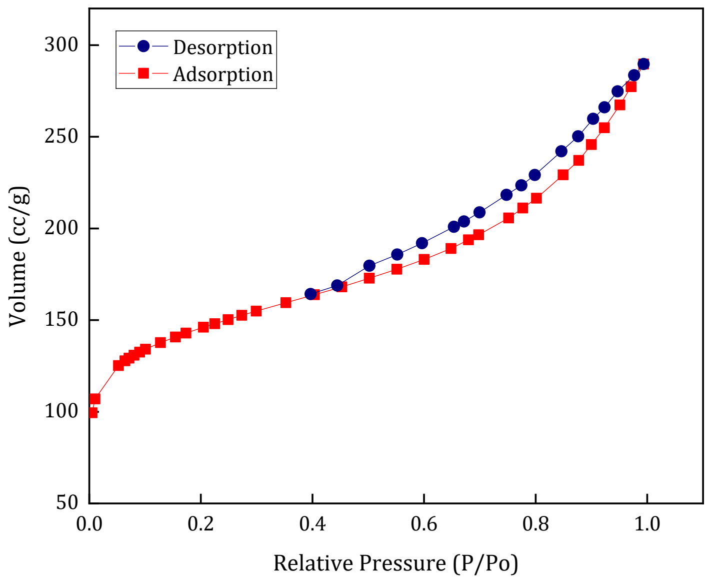
Fig. 4 illustrates the N_2 adsorption–desorption isotherm of raw banana stem (RBS), which displayed characteristics of a Type III isotherm as per IUPAC categorisation, marked by minimal nitrogen absorption over the whole relative pressure range and the lack of a prominent knee at low P/P_0. This trend indicates poor adsorbate–adsorbent interactions and a deficiency of substantial microporosity, typical for non-activated lignocellulosic biomass. The activated carbon banana stem (ACBS) displayed a Type IV isotherm with an H3 hysteresis loop, indicating the formation of a mesoporous structure by slit-shaped pores. The surface area and total pore volume of ACBS were markedly superior to those of the raw material, substantiating that chemical activation successfully eliminated volatiles and improved porosity. Because of increased molecular diffusion and the availability of adsorption sites, these mesoporous structures are suitable for adsorbing dye molecules such as Reactive Black 5. These findings are consistent with prior investigations on banana-derived adsorbents. Activated banana peel carbons exhibit BET surface areas ranging from 289.86 m^2/g with Type IV isotherms [30].

Table 3 *Pore characteristics of RBS and ACBS based on BET analysis*

Material	Surface Area (m^2/g)	Pore Volume (cm^3/g)	Pore Diameter (nm)
RBS	1.886	0.0047	9.882
ACBS	475.7	0.4491	3.776



(a)



(b)

Fig. 4 *Nitrogen adsorption–desorption isotherm of (a) RBS; and (b) ACBS*

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3.5 Dye Removal of Raw and Activated Banana Stems

The effectiveness of raw and activated banana stems in adsorption can be observed from the removal of RB_5 dye. The removal study reveals that both materials can adsorb dye molecules. However, their efficiencies vary significantly. Similar results have been reported for various biomass-based adsorbents, including rice husk, where activation significantly improved dye uptake [34]. Fig. 5 indicates that ACBS removes more dye than RBS; its removal efficiency is 99.11%, whereas RBS is 6.4%. Fig. 6 shows the visual comparison of RB_5 dye removal using RBS and ACBS. This significant difference emphasises the impact of chemical activation in enhancing adsorption performance. The higher removal efficiency reported for ACBS implies not only increased adsorption but also better structural compatibility with large dye molecules such as RB_5 [35]. The result is the outcome of the activation process, which increases the surface area, porosity, and availability of organic functional groups that are helpful in the adsorption of dyes [36].

ACBS has a higher adsorption capacity (16.52 mg/g) than RBS (1.07 mg/g), suggesting that it can hold more dye molecules per unit mass. However, RBS exhibits a low sorption capacity and poor physical stability without any modification [37]. This is consistent with prior studies indicating that untreated lignocellulosic materials often lack adequate porosity and stability for successful dye removal due to their compact structure and limited active sites [38]. The adsorption efficiency of ACBS (99.11%) achieved in this study is comparable to that of other biomass-derived activated carbons. For example, palm shell-based activated carbon removed 96.7% of RB_5 under identical conditions [39].

These findings indicate that chemical activation not only improves the material's proximate characteristics (higher fixed carbon, lower volatile matter) but also significantly enhances adsorption performance. In terms of application, ACBS may be an efficient, low-cost adsorbent for textile wastewater treatment, particularly in underdeveloped countries where banana production produces substantial volumes of agricultural leftovers.

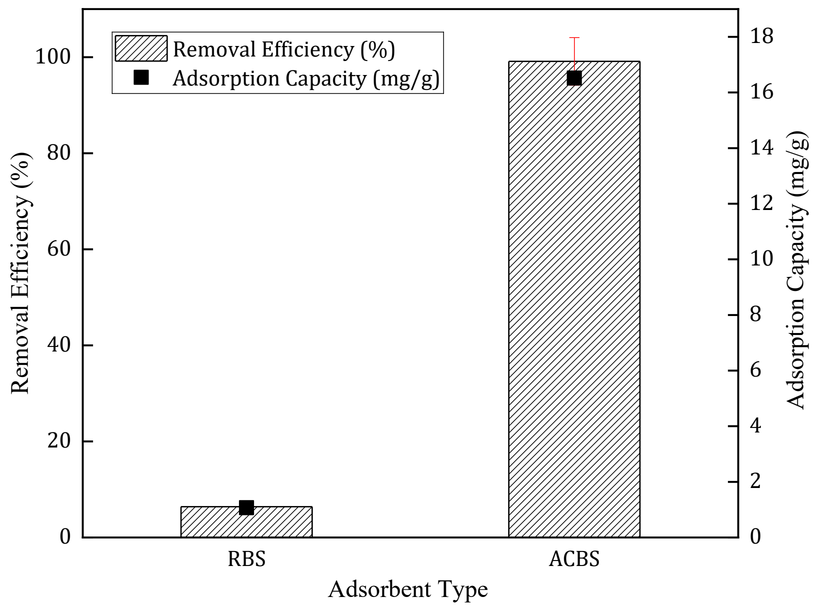

Fig. 5 *Removal efficiency and adsorption capacity of RBS and ACBS*

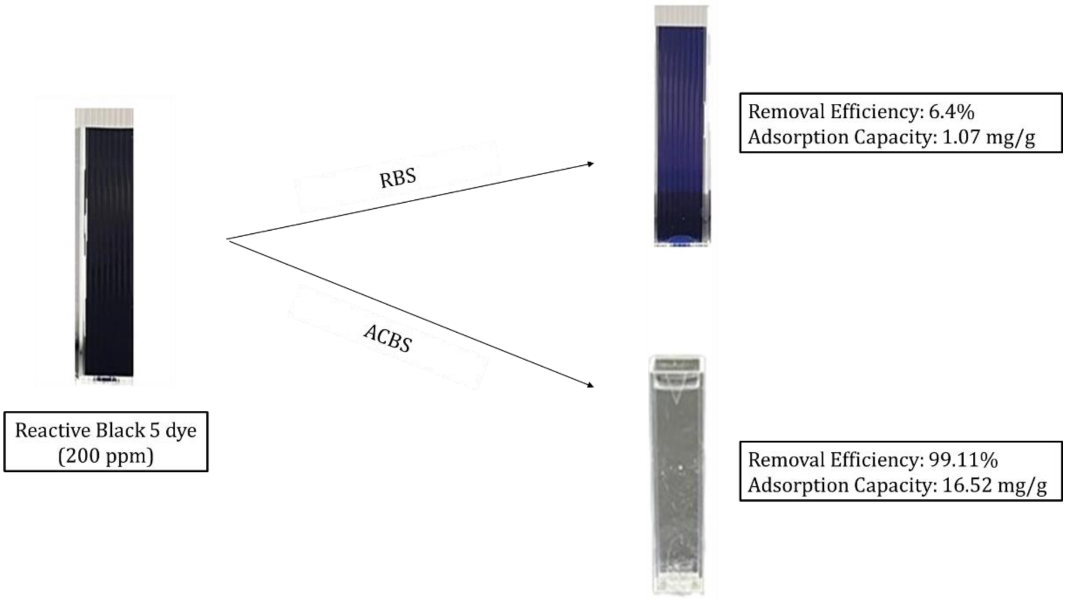

Fig. 6 *Visual comparison of RB5 dye removal using RBS and ACBS*

4. Conclusion

Raw and activated carbon impregnated with H_3PO_4 derived from banana stems were successfully produced. Proximate analysis of RBS and ACBS showed considerable changes resulting from the activation procedure, with ACBS having 36.4% more fixed carbon than RBS (5.68%). These findings showed that the activation process effectively increased carbon content and porosity, making ACBS suitable for adsorption applications. Based on SEM, ACBS were more porous than RBS due to chemical activation, resulting in a higher surface area and larger pore volume, thereby improving adsorption efficiency. FTIR also showed a difference, with more peaks in RBS than ACBS. BET analysis revealed the surface area, pore volume, and average pore diameter of the ACBS (475.7 m^2/g, 0.4491 cm3/g, and 3.776 nm), which were significantly greater than those of RBS (1.886 m^2/g, 0.0047 cm^3/g, and 9.882 nm), demonstrating effective pore development during activation. Finally, the effectiveness of this adsorbent had been observed, and it could be concluded that ACBS, with a removal efficiency of 99.11%, was much better than RBS, with only 6.4%.

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Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Nur Atikah Rejab;* ***Data collection:*** *Nur Atikah Rejab;* ***Analysis and interpretation of results:*** *Nur Atikah Rejab, Farah Naemah Mohd Saad;* ***Draft manuscript preparation:*** *Nur Atikah Rejab, Farah Naemah Mohd Saad, Tengku Nuraiti Tengku Izhar;* ***Supervision:*** *Farah Naemah Mohd Saad, Tengku Nuraiti Tengku Izhar, Achmad Syafiuddin. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Al-Tohamy, R., Ali, S. S., Li, F., Okasha, K. M., Mahmoud, Y. A. G., Elsamahy, T., Jiao, H., Fu, Y., & Sun, J. (2022). A critical review on the treatment of dye-containing wastewater: Ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety. Ecotoxicology and Environmental Safety, 231, 113160. https://doi.org/10.1016/j.ecoenv.2021.113160

[2] Yağmur, H. K., & Kaya, İ. (2021). Synthesis and characterization of magnetic ZnCl2-activated carbon produced from coconut shell for the adsorption of methylene blue. Journal of Molecular Structure, 1232, 130071. https://doi.org/10.1016/j.molstruc.2021.130071

[3] Elnabi, M. K. A., Ghazy, M. A., Ali, S. S., Eltarahony, M., & Nassrallah, A. (2025). Efficient biodegradation and detoxification of reactive black 5 using a newly constructed bacterial consortium. Microbial Cell Factories, 24, 154. https://doi.org/10.1186/s12934-025-02768-z

[4] El Bouraie, M., & El Din, W. S. (2016). Biodegradation of Reactive Black 5 by Aeromonas hydrophila strain isolated from dye-contaminated textile wastewater. Sustainable Environment Research, 26, 209-216. https://doi.org/10.1016/j.serj.2016.04.014

[5] Bektas, T. E., & Eren, F. (2019). Batch and column studies for removal of sulphate from real wastewater using ion exchange resin. Sakarya University Journal of Science, 23, 810-816. https://doi.org/10.16984/saufenbilder.538174

[6] Selvakumar, S., Manivasagan, R., & Chinnappan, K. (2013). Biodegradation and decolourization of textile dye wastewater using Ganoderma lucidum. 3 Biotech, 3, 71-79. https://link.springer.com/article/10.1007/s13205-012-0073-5

[7] Periyasamy, A. P. (2024). Recent advances in the remediation of textile-dye-containing wastewater: Prioritizing human health and sustainable wastewater treatment. Sustainability, 16, 141-157. https://doi.org/10.3390/su16020495

[8] Zheng, X., & Xu, L. (2024). Research progress of printing and dyeing wastewater treatment. Journal of Sustainable Civil Engineering and Technology, 3, 141–157. doi: 10.24191/jscet.v3i2.141-157

[9] Dutta, S., Gupta, B., Srivastava, S. K., & Gupta, A. K. (2021). Recent advances on the removal of dyes from wastewater using various adsorbents: a critical review. Materials Advances, 2, 4497-4531. https://doi.org/10.1039/D1MA00354B

[10] Kathing, C., & Saini, G. (2022). A review of various treatment methods for the removal of dyes from textile effluent. Recent Progress in Materials, 04, 1-15. https://doi.org/10.21926/rpm.2204028

[11] Ayadi, I., & Souissi, Y. (2015). Chemical synonyms, molecular structure and toxicological risk assessment of synthetic textile dyes: A critical review. Journal of Developing Drugs, 5, 1000151. doi:10.4172/2329-6631.1000151

[12] Jjagwe, J., Olupot, P. W., Menya, E., & Kalibbala, H. M. (2021). Synthesis and application of granular activated carbon from biomass waste materials for water treatment: A review. Journal of Bioresources and Bioproducts, 6, 292-322. https://doi.org/10.1016/j.jobab.2021.03.003

[13] Ben-Mansour, R., & Qasem, N. A. A. (2018). An efficient temperature swing adsorption (TSA) process for separating CO2 from CO2/N2 mixture using Mg-MOF-74. Energy Conversion and Management, 156, 10-24. https://doi.org/10.1016/j.enconman.2017.11.010

[14] Chew, T. W., H'Ng, P. S., Luqman Chuah Abdullah, B. C. T. G., Chin, K. L., Lee, C. L., Mohd Nor Hafizuddin, B. M. S., & TaungMai, L. (2023). A review of bio-based activated carbon properties produced from different activating chemicals during chemicals activation process on biomass and its potential for Malaysia. Materials, 16, 7365. https://doi.org/10.3390/ma16237365

[15] Feng, P., Li, J., Wang, H., & Xu, Z. (2020). Biomass-based activated carbon and activators: Preparation of activated carbon from corncob by chemical activation with biomass pyrolysis liquids. ACS Omega, 5, 24064-24072. https://doi.org/10.1021/acsomega.0c03494

[16] Neme, I., Gonfa, G., & Masi, C. (2022). Activated carbon from biomass precursors using phosphoric acid: A review. Heliyon, 8, e11940. https://doi.org/10.1016/j.heliyon.2022.e11940

[17] Guerrero-Pérez, M. O., Valero-Romero, M. J., Hernández, S., Nieto, J. M. L., Rodríguez-Mirasol, J., & Cordero, T. (2012). Lignocellulosic-derived mesoporous materials: An answer to manufacturing non-expensive catalysts useful for the biorefinery processes. Catalysis Today, 195, 155-161. https://doi.org/10.1016/j.cattod.2012.03.068

[18] Yogamalar, N. R., Chithambararaj, A., & Mathi, D. B. (2025). Advancing sustainability through biomass-derived carbon activation for high porosity and surface area in electrochemical capacitance. Journal of Power Sources, 647, 237324. https://doi.org/10.1016/j.jpowsour.2025.237324

[19] Jadhav, A. C., & Jadhav, N. C. (2021). Treatment of textile wastewater using adsorption and adsorbents. Sustainable Technologies for Textile Wastewater Treatments. Elsevier, pp. 235-273. https://doi.org/10.1016/B978-0-323-85829-8.00008-0

[20] Misran, E., Bani, O., Situmeang, E. M., & Purba, A. S. (2022). Banana stem based activated carbon as a low-cost adsorbent for methylene blue removal: Isotherm, kinetics, and reusability. Alexandria Engineering Journal, 61, 1946-1955. https://doi.org/10.1016/j.aej.2021.07.022

[21] Ai, B., Zheng, L., Li, W., Zheng, X., Yang, Y., Xiao, D., Shi, J., & Sheng, Z. (2021). Biodegradable cellulose film prepared from banana pseudo-stem using an ionic liquid for mango preservation. Frontiers in Plant Science, 12, 625878. https://doi.org/10.3389/fpls.2021.625878

[22] Aziz, A. R. A., Md Ali, A. H., Tamunaidu, P., Huzir, N. M., Rosly, M. B., Azhari, A. H., & Shamsulbahrin, S. (2023). Banana stem based activated carbon as a low-cost adsorbent for Pb(ii) ion removal. Semarak Engineering Journal, 2, 8-14. https://doi.org/10.37934/sej.2.1.814b

[23] Mkilima, T., Zharkenov, Y., Abduova, A., Sarypbekova, N., Kudaibergenov, N., Sakanov, K., Zhukenova, G., Omarov, Z., Sultanbekova, P., & Kenzhaliyeva, G. (2024). Utilization of banana peel-derived activated carbon for the removal of heavy metals from industrial wastewater. Case Studies in Chemical and Environmental Engineering, 10, 100791. https://doi.org/10.1016/j.cscee.2024.100791

[24] Fito, J., Tibebu, S., & Nkambule, T. T. I. (2023). Optimization of Cr (VI) removal from aqueous solution with activated carbon derived from Eichhornia crassipes under response surface methodology. BMC Chemistry, 17, 4. https://doi.org/10.1186/s13065-023-00913-6

[25] Kansal, S. K., Kaur, N., & Singh, S. (2009). Photocatalytic degradation of two commercial reactive dyes in aqueous phase using nanophotocatalysts. Nanoscale Research Letters, 4, 709. https://doi.org/10.1007/s11671-009-9300-3

[26] Silva, M. C., Spessato, L., Silva, T. L., Lopes, G. K. P., Zanella, H. G., Yokoyama, J. T. C., Cazetta, A. L., & Almeida, V. C. (2021). H3PO4–activated carbon fibers of high surface area from banana tree pseudo-stem fibers: Adsorption studies of methylene blue dye in batch and fixed bed systems. Journal of Molecular Liquids, 324, 114771. https://doi.org/10.1016/j.molliq.2020.114771

[27] Ma, Z., Yang, Y., Wu, J., Xu, J., Peng, H., Liu, X., Zhang, W., & Wang, S. (2019). In-depth comparison of the physicochemical characteristics of bio-char derived from biomass pseudo components: Hemicellulose, cellulose, and lignin. Journal of Analytical and Applied Pyrolysis, 140, 195-204. https://doi.org/10.1016/j.jaap.2019.03.015

[28] Suhas, Gupta, V. K., Carrott, P. J. M., Singh, R., Chaudhary, M., & Kushwaha, S. (2016). Cellulose: A review as natural, modified and activated carbon adsorbent. Bioresource Technology, 216, 1066-1076. https://doi.org/10.1016/j.biortech.2016.05.106

[29] Misran, E., Bani, O., Situmeang, E. M., & Purba, A. S. (2022). Banana stem based activated carbon as a low-cost adsorbent for methylene blue removal: Isotherm, kinetics, and reusability. Alexandria Engineering Journal, 61, 1946-1955. https://doi.org/10.1016/j.aej.2021.07.022

[30] Hussain, O. A., Hathout, A. S., Abdel-Mobdy, Y. E., Rashed, M. M., Abdel Rahim, E. A., & Fouzy, A. S. M. (2023). Preparation and characterization of activated carbon from agricultural wastes and their ability to remove chlorpyrifos from water. Toxicology Reports, 10, 146-154. https://doi.org/10.1016/j.toxrep.2023.01.011

[31] Ullah, S., Shah, S. S. A., Altaf, M., Hossain, I., El Sayed, M. E., Kallel, M., El-Bahy, Z. M., ur Rehman, A., Najam, T., & Nazir, M. A. (2024). Activated carbon derived from biomass for wastewater treatment: Synthesis, application and future challenges. Journal of Analytical and Applied Pyrolysis, 179, 106480. https://doi.org/10.1016/j.jaap.2024.106480

[32] Misran, E., Bani, O., Situmeang, E. M., & Purba, A. S. (2022). Banana stem based activated carbon as a low-cost adsorbent for methylene blue removal: Isotherm, kinetics, and reusability. Alexandria Engineering Journal, 61, 1946-1955. https://doi.org/10.1016/j.aej.2021.07.022

[33] Tomczyk, A., Sokołowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: Pyrolysis temperature and feedstock kind effects. Reviews in Environmental Science and Bio/Technology, 19, 191-215. https://doi.org/10.1007/s11157-020-09523-3

[34] Bai, W., Qian, M., Li, Q., Atkinson, S., Tang, B., Zhu, Y., & Wang, J. (2021). Rice husk-based adsorbents for removing ammonia: Kinetics, thermodynamics and adsorption mechanism. Journal of Environmental Chemical Engineering, 9, 105793. https://doi.org/10.1016/j.jece.2021.105793

[35] Samarghandy, M. R., Hoseinzade, E., Taghavi, M., & Hoseinzadeh, S. (2011). Biosorption of Reactive Black 5 from aqueous solution using acid-treated biomass from potato peel waste. BioResources, 6, 4840-4855. https://doi.org/10.15376/biores.6.4.4840-4855

[36] Akhtar, M. S., Ali, S., & Zaman, W. (2024). Innovative adsorbents for pollutant removal: Exploring the Latest research and applications. Molecules, 29, 431. https://doi.org/10.3390/molecules29184317

[37] Mohammed, I. A., Mohamad, F., & Salamun, N. (2022). Activated carbon derived from banana stem waste for adsorption of crystal violet. Proceedings of Science and Mathematics, 14, 18-26.

[38] Yadav, M., Singh, N., Annu, Khan, S. A., Raorane, C. J., & Shin, D. K. (2024). Recent advances in utilizing lignocellulosic biomass materials as adsorbents for textile dye removal: A comprehensive review. Polymers, 16, 2417. https://doi.org/10.3390/polym16172417

[39] Giannakoudakis, D. A., Kyzas, G. Z., Avranas, A., & Lazaridis, N. K. (2016). Multi-parametric adsorption effects of the reactive dye removal with commercial activated carbons. Journal of Molecular Liquids, 213, 381-389. https://doi.org/10.1016/j.molliq.2015.07.010