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Batch Adsorption Performance of a KOH-Activated Corn Cob Carbon–Calcined Fly Ash Composite for Multi-Pollutant Removal

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Abstract

The discharge of dye and heavy metal-containing wastewater remains a major environmental challenge, highlighting the need for low-cost, effective adsorbents. This study evaluated the batch adsorption performance of a composite adsorbent KOH-activated corn cob carbon combined with calcined coal fly ash toward methylene blue (MB), cadmium (Cd^{2+}), and hexavalent chromium (Cr(VI)). Corn cob carbon was prepared via carbonization and KOH activation, while fly ash was calcined before composite preparation. SEM-EDS and BET analyses characterized the adsorbent's physicochemical properties. KOH activation raised the corn cob carbon's surface area from 8.80 to 40.88 m^2/g, while calcination increased the fly ash's surface area from 0.32 to 1.65 m^2/g, indicating improved surface development. Under optimum conditions (5:1 fly ash-to-carbon ratio, 90-mesh particle size), the composite achieved removal efficiencies of 99.39% for MB (0.40 mg/g) and 99.56% for Cd^{2+} (1.659 mg/g), showing strong performance toward cationic pollutants. Cr(VI) removal, however, reached only 25.37% (1.723 mg/g), likely due to unfavorable electrostatic interactions between the adsorbent surface and anionic chromium species under the tested conditions. Overall, the composite showed promising adsorption performance for cationic contaminants, while further modification is needed to improve its effectiveness against anionic pollutants like Cr(VI).

Keywords: Corn cob activated carbon, fly ash, cadmium, chromium(VI), methylene blue.

INTRODUCTION

Water pollution from synthetic dyes and heavy metals in industrial wastewater has been a major environmental concern over the past few decades. Approximately 80% of dye-containing wastewater is still discharged into water bodies without adequate treatment, degrading aquatic environmental quality (Lin et al., 2023). Methylene blue (MB) is among the most common cationic synthetic dyes; it is toxic, persistent, resistant to biodegradation, and can reduce light penetration, thereby disrupting photosynthesis in aquatic organisms (Oladoye et al., 2022).

Beyond dyes, industrial wastewater frequently contains heavy metals such as hexavalent chromium (Cr(VI)) and cadmium (Cd^{2+}), which mainly originate from electroplating, tanning, and metal manufacturing industries (Irshad et al., 2023). Cr(VI) is carcinogenic and toxic; concentrations exceeding the 0.05 mg/L quality standard can contaminate water bodies and harm both aquatic organisms and humans (Kerur et al., 2021).

Cadmium in industrial wastewater can infiltrate soil and be taken up by plants and the human body, causing health problems such as liver and kidney damage, reproductive disorders, and cancer (Gong et al., 2022). The maximum permissible exposure limits for Cd^{2+} in drinking water have been set at <0.005 mg/L by the USEPA and 3 ppb by the WHO (Modwi et al., 2025).

A simple and efficient method is therefore needed to remove these dyes and heavy metals from wastewater. Various methods have been used to date, including chemical precipitation, ion exchange, solvent extraction, membrane filtration, and electrochemical treatment. However, these methods have drawbacks such as incomplete removal, high operating costs, high energy consumption, and

secondary pollution.

Adsorption is an effective and economical approach for treating such wastewater. Corn cob has potential as an activated carbon precursor, containing 43.42% carbon with a calorific value of 14.7–18.9 MJ/kg (Sufyan et al., 2026), while national corn production, which reached 23.6 million tons in 2023, leaves more than 40% of the resulting organic waste underutilized (Barkah et al., 2025). Coal fly ash (FA), rich in SiO_2 and Al_2O_3, also has potential as an adsorbent owing to its aluminosilicate content (Jadaa, 2024). Most studies to date have focused on using fly ash to remove pollutants such as dyes and metal ions from wastewater (B. Liu et al., 2023).

Previous studies have reported MB adsorption efficiencies of up to 99.03% using corn cob activated carbon (CC-AC) (Aritonang et al., 2025) and Cr(VI) removal efficiencies of up to 99.45% using KOH-activated corn cob activated carbon (Zegeye et al., 2025), while fly ash has been reported to reduce MB by up to 97.1% (Dinh et al., 2021). Unlike previous studies that generally investigated either activated carbon or fly ash separately for the adsorption of individual pollutants, this work develops a composite adsorbent consisting of KOH-activated corn cob carbon and calcined coal fly ash and evaluates its adsorption performance toward different classes of contaminants, including a cationic dye (MB), a divalent heavy metal (Cd^{2+}), and an anionic heavy metal species (Cr(VI)). This study also compares the adsorption behavior of cationic and anionic pollutants under identical operating conditions, providing insight into the adsorption selectivity of the composite adsorbent. This study aims to evaluate the adsorption performance of a KOH-activated corn cob carbon–calcined fly ash composite toward methylene blue, Cd(II), and Cr(VI), and to relate the adsorption performance to the physical characteristics (SEM-EDS, BET) of the adsorbent.

METHODS

Materials and Equipment

The raw materials used were corn cobs from Batujajar, Bandung, and coal fly ash from PT. Safilindo Permata, Bandung Regency. The chemicals used included pro-analysis (PA) grade KOH as the activator, PA-grade methylene blue as the source of synthetic MB wastewater, $K_2Cr_2O_7$ solution as the source of synthetic Cr(VI), real Cr(VI) wastewater from PT. Jabil Circuit Indonesia, $Cd(NO_3)_2{\cdot}4H_2O$ as the source of synthetic Cd^{2+}, and other PA-grade analytical reagents.

The main instruments used were a Labo Single Beam UV-Vis spectrophotometer, GBC Scientific SavantAA Atomic Absorption Spectrophotometer AAS Flame, a Hitachi SU3500 Scanning Electron Microscope equipped with Energy Dispersive Spectroscopy (SEM-EDS), and a Nova 1000 Quantachrome Brunauer–Emmett–Teller (BET) surface area analyzer.

Adsorbent Preparation

Corn cobs were washed, dried, cut to approximately 5 mm, and carbonized at 600°C for 3 hours (Aritonang et al., 2025). The resulting carbon was activated with 1 M KOH solution at a 1:10 (w/v) ratio, agitated at 60°C for 30 minutes (Sankaranarayanan et al., 2025), soaked for 25 hours at room temperature, washed with 0.1 M HCl and distilled water until neutral pH, dried at 105°C, and ground into powder (Zegeye et al., 2025). Fly ash was washed, dried, and calcinated in a furnace at 500°C for 1 hour (D. Liu et al., 2019), then ground to 325 mesh.

Batch Adsorption Procedure

Batch adsorption was carried out by mixing 100 mL of wastewater with the fly ash (FA)–corn cob activated carbon (CC-AC) composite adsorbent at a total adsorbent mass of 6 g (Hummadi et al., 2022), agitated at 200 rpm for 60 minutes (Yaashikaa & Saravanan, 2026; Zegeye et al., 2025). All experiments were conducted at room temperature (without external heating or temperature control). The initial pH of each wastewater was not adjusted and was left at its native condition, following the natural pH of each solution. The measured initial pH values were approximately 7 (neutral) for the MB wastewater, 4.00 for the Cr(VI) wastewater, and 5.00 for the Cd^{2+} wastewater. Synthetic wastewater containing MB was used at a concentration of 25 ppm, and Cd^{2+} was used at a concentration of 100 ppm, while the real Cr(VI) wastewater was diluted 100×. MB wastewater was tested at FA:CC-AC mass ratios of 0:6, 1:5, 2:4, 3:3, 4:2, 5:1, and 6:0, followed by CC-AC particle size variations of 60, 70, 80, 90, and 100 mesh. Once the best conditions were identified, they were applied to the batch adsorption of Cd^{2+} and Cr(VI) wastewater. Each experimental condition was conducted in duplicate using independent experimental runs ($n = 2$) to verify the repeatability of the experimental results. The reported values represent the arithmetic mean of the two replicates.

Adsorbent Characterization (SEM-EDS and BET)

The surface morphology of the carbon and fly ash before and after activation/calcination was observed by SEM at 1000× and 5000× magnification, while the surface elemental composition was

analyzed by EDS. The specific surface area of the adsorbents was determined by the BET method using a porosimeter.

Concentration Analysis and Calculation

Residual MB concentration was analyzed using a UV-Vis spectrophotometer at λmax 664 nm following the method of (Hulupi et al., 2023), while Cr(VI) concentration was determined according to SNI 6989.71:2009 using the diphenylcarbazide method at 530–540 nm, and Cd^{2+} concentration was determined according to SNI 6989.16:2009 using atomic absorption spectrophotometry (AAS) at a wavelength of 228.8 nm. The removal percentage and adsorption capacity were calculated using Equations (1) and (2):

$$\%\text{Removal} = \left(\frac{C_0 - C_e}{C_0}\right) \times 100\% \quad (1)$$

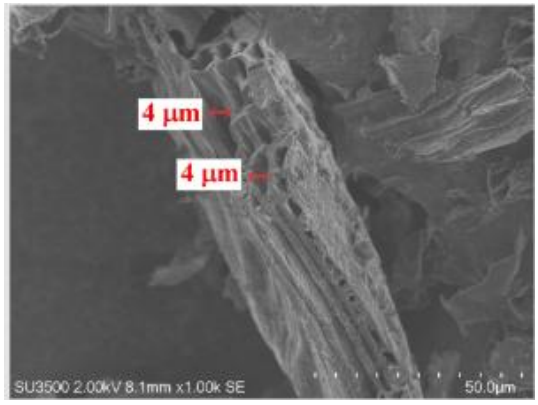
$$q_e = \frac{(C_0 - C_e) \times V}{m} \quad (2)$$

where Co and Ce are the initial and equilibrium adsorbate concentrations (mg/L), V is the solution volume (L), and m is the adsorbent mass (g).

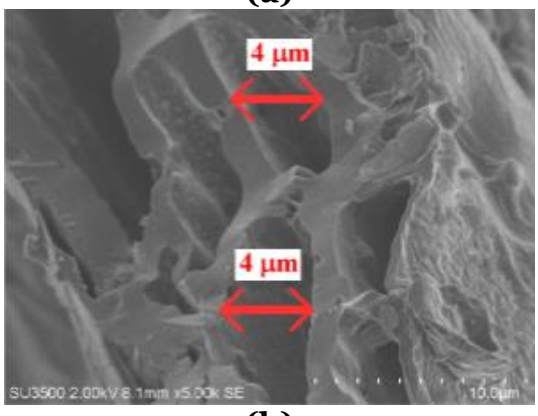
RESULTS AND DISCUSSION

SEM-EDS Characterization

SEM images of corn cob carbon before and after KOH activation are shown in Figure 1.



(a)



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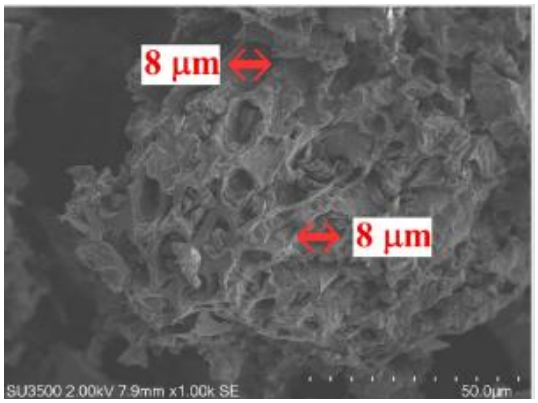

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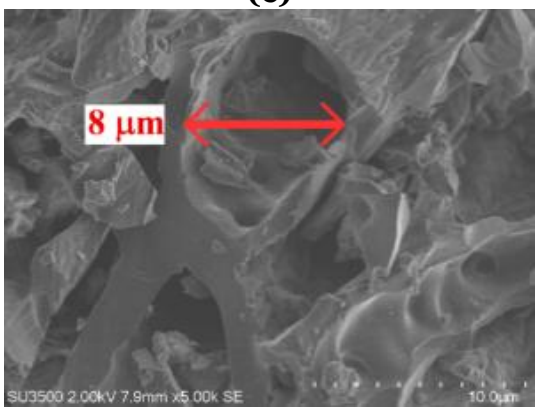


(d)

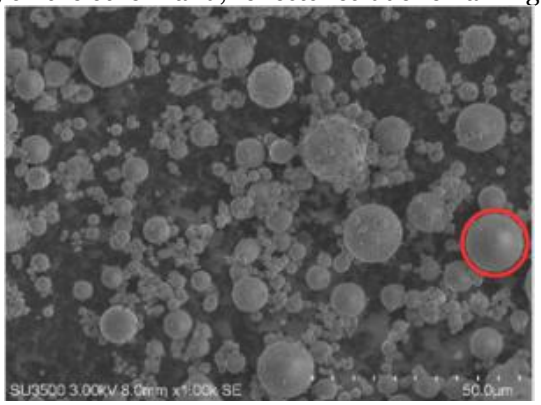
Figure 1. SEM images of corn cob carbon and activated carbon: (a) carbon at 1000× magnification, (b) carbon at 5000× magnification, (c) activated carbon at 1000× magnification, and (d) activated carbon at 5000× magnification

The unactivated carbon displayed the elongated fibrous structure typical of lignocellulose, with closed cavities of about 4 µm, whereas after KOH activation the surface became rougher and more porous, with cavity sizes of about 8 µm. This change occurs because KOH reacts with carbon atoms at high temperature to form potassium compounds that intercalate the carbon structure; when these compounds are washed out during purification, new cavities form that enlarge the pore volume (Williams et al., 2022).

Table 1. EDS results for corn cob carbon before and after KOH activation

Element	%Weight	
	Carbon	Activated Carbon
C	84.35	97.63
O	11.92	-
Na	-	0.52
Si	2.78	0.81
K	0.96	1.05

The EDS data in Table 1 support this interpretation: carbon content increased sharply from 84.35% to 97.63%, while oxygen decreased to below the detection limit and Si content declined, indicating successful carbonization and activation in removing or reducing non-carbon compounds. The increase in K content, on the other hand, reflects residue remaining from KOH activation.



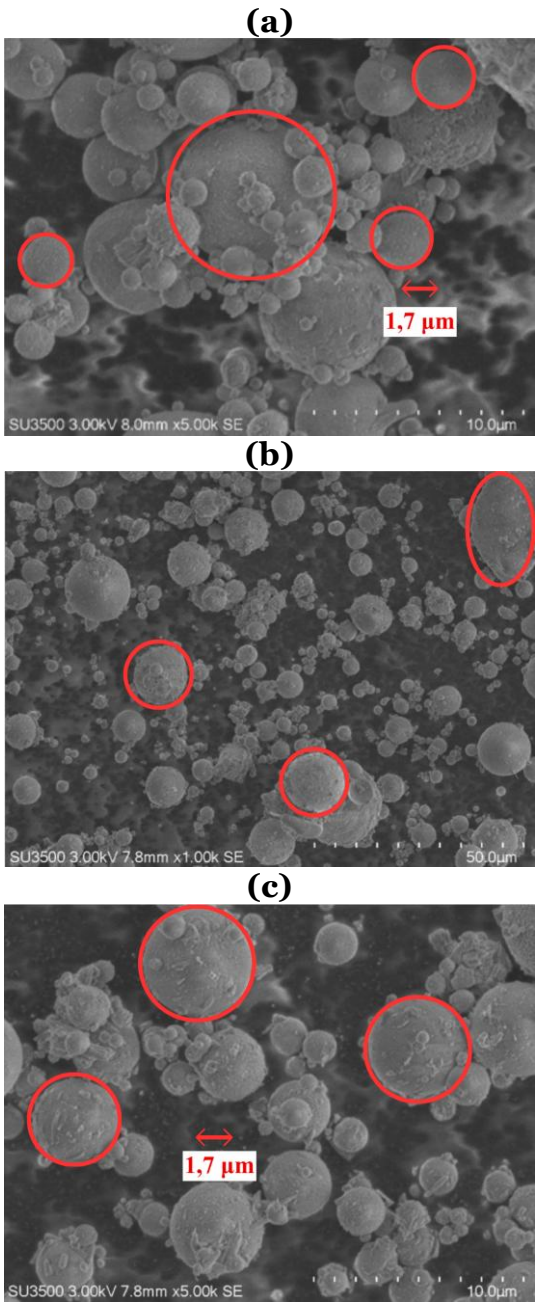


Figure 2. SEM images of raw and calcined fly ash: (a) fly ash at 1000× magnification, (b) fly ash at 5000× magnification, (c) calcined fly ash at 1000× magnification, and (d) calcined fly ash at 5000× magnification

SEM images of fly ash before and after calcination are shown in Figure 2. The raw fly ash displayed a spherical (cenosphere) morphology with a relatively smooth surface, whereas after calcination the particles retained their spherical shape and a diameter of about 1.7 µm, but their surface became rougher and more porous. This indicates that calcination modifies the surface characteristics without substantially altering the particles's basic morphology.

Table 2. EDS results for fly ash before and after calcination

Element	%Weight	
	Fly Ash	Calcined Fly Ash
C	-	0.50
O	50.44	53.32
Na	-	1.94
Mg	4.27	1.92
Al	4.78	15.31
Si	12.47	21.89
S	4.44	-
K	-	2.00

Ca	18.82	2.89
Fe	4.81	1.25

The fly ash EDS data (Table 2) show that after calcination, silica content increased from 12.47% to 21.89% and aluminum from 4.78% to 15.31%, while calcium decreased sharply from 18.82% to 2.89% and sulfur disappeared entirely. This pattern suggests that calcination decomposes sulfur-, calcium-, and iron-containing phases, thereby relatively enriching a more thermally stable aluminosilicate framework, consistent with the finding of Kutchko and Kim (Kutchko & Kim, 2006) that coal fly ash is predominantly composed of amorphous aluminosilicate spheres.

BET Characterization

The BET results for corn cob carbon and coal fly ash before and after treatment are shown in Table 3.

Table 3. BET results for corn cob carbon and fly ash

Sample	Before Treatment ($\frac{m^2}{g}$)	After Activation/ Calcination ($\frac{m^2}{g}$)
Corn Cob Carbon	8.80	40.88
Coal Fly Ash	0.32	1.65

Activation using KOH increases the specific surface area of corn cob carbon from 8.80 to 40.88 m^2/g or about 4.6 times. This increase indicates that the activation process successfully developed the carbon pore structure through the reaction between KOH and the carbon matrix, resulting in an etching process that removed volatile compounds and impurities covering the surface, followed by the formation and widening of pores that increased the adsorbent's surface area (Williams et al., 2022). This result is consistent with the SEM observations, which showed a rougher and more porous surface after KOH activation, confirming the successful development of the adsorbent's textural properties. Nevertheless, the specific surface area obtained is still lower compared to commercial activated carbon, which generally has a surface area of 950–2000 m^2/g, depending on the raw materials and activation methods used (Mohd Azmi et al., 2022). The difference is suspected to be related to the preparation conditions used, as the development of the pore structure is influenced by the ratio of activator to precursor, activation temperature, activation time, and burn-off rate. The increase in specific surface area due to higher activation temperatures has also been reported, from 120.72 to 926.07 m^2/g when the activation temperature of corn cob carbon was increased from 600 to 800 °C. Therefore, the BET value obtained in this study more accurately reflects the consequences of the chosen preparation conditions rather than the ineffectiveness of the activation process (Wang et al., 2022; Williams et al., 2022).

On the contrary, the calcination process increases the specific surface area of coal fly ash from 0.3171 to 1.6462 m^2/g or about 5.2 times. This increase indicates that thermal treatment can improve the surface characteristics of fly ash by removing adsorbed water and some unburned carbon, thereby increasing the accessible surface area (Ram & Mohanty, 2022). However, the specific surface area obtained is still relatively low, which is suspected to be influenced by the initial characteristics of the fly ash, such as particle size, morphology, and mineral composition. As a result, the calcination process plays a more significant role in cleaning the surface and opening existing pores rather than forming new pore networks (Ram & Mohanty, 2022). Therefore, the contribution of fly ash to adsorption is likely influenced not only by its textural properties but also by the availability of mineral-based active sites on its surface.

Overall, KOH activation and calcination have been proven to enhance the textural characteristics of the adsorbent through an increase in specific surface area. However, the interpretation of BET results is not solely based on specific surface area; it also needs to consider other pore texture parameters, such as pore volume and pore size distribution, because adsorption efficiency is influenced by the combination of pore structure characteristics and the surface properties of the adsorbent. Therefore, the BET characterization in this study provides a basis for understanding the physical characteristics of the adsorbent before relating them to its adsorption performance in the subsequent discussion (Choma et al., 2024; Williams et al., 2022). These improvements in textural properties are expected to increase the accessibility of adsorption sites, while the influence of these characteristics on the adsorption behavior of MB, Cd^{2+}, and Cr(VI) is discussed in the following sections.

Batch Adsorption of Methylene Blue

The effect of the fly ash-to-corn cob activated carbon (FA:CC-AC) mass ratio on the adsorption capacity and % removal of MB is shown in Figure 3.

Starting from the FA:CC-AC ratio of 0:6 (corn cob activated carbon alone), the adsorption capacity and removal efficiency were 0.36 mg/g and 88.99%, respectively. Both the adsorption capacity and % removal increased with increasing fly ash proportion, reaching an optimum at a 5:1 ratio (0.40 mg/g and 99.80%, respectively), before decreasing for fly ash alone (6:0) to 0.26 mg/g and 64.65%.

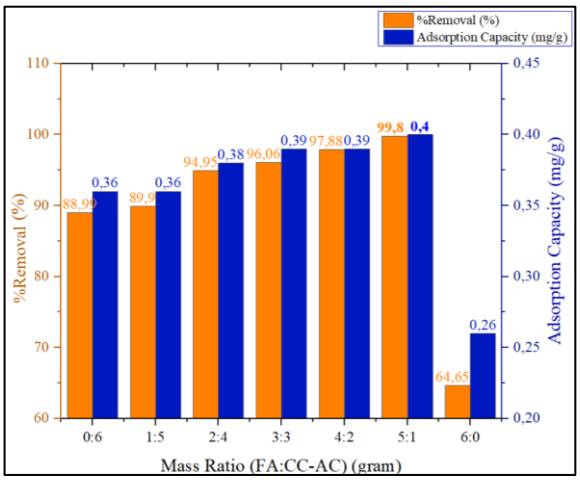


Figure 3. Adsorption capacity and % removal of methylene blue at varying fly ash-to-activated-carbon mass ratios

The combination of both materials performed better than either alone because the activated carbon contributes a high surface area while the fly ash provides additional active sites through its aluminosilicate components (Choma et al., 2024). This phenomenon is illustrated in Figure 4.

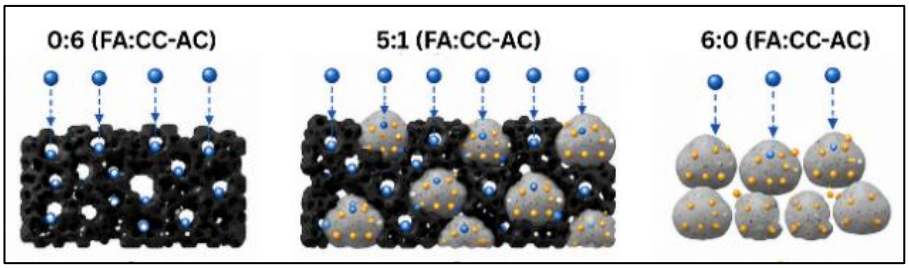


Figure 4. Schematic illustration of the complementary adsorption roles of KOH-activated corn cob carbon and calcined fly ash in the composite adsorbent

In general, adsorption efficiency is influenced by the characteristics of the adsorbent, particularly its specific surface area, pore volume, pore size distribution, and surface functional groups. A higher specific surface area provides more accessible adsorption sites for adsorbate molecules, thereby enhancing the adsorption performance (Choma et al., 2024). This explains why corn cob activated carbon at the FA:CC-AC ratio of 0:6 exhibited a relatively high adsorption capacity of 0.36 mg/g with a removal efficiency of 88.99%. BET characterization confirmed that KOH activation significantly increased the specific surface area of the activated carbon, while SEM images revealed a rougher surface morphology and a more developed pore structure after activation. These structural improvements facilitated the diffusion of methylene blue molecules toward the available adsorption sites, resulting in enhanced adsorption performance.

Nevertheless, increasing the fly ash content to the optimum FA:CC-AC ratio of 5:1 further improved the adsorption capacity to 0.40 mg/g with a removal efficiency of 99.80%. EDS analysis showed that calcination increased the Si and Al contents of the fly ash, indicating a greater predominance of the aluminosilicate phase. Silica (SiO_2) and alumina (Al_2O_3) are recognized as important components contributing to the adsorptive properties of fly ash (Sylvia et al., 2023). Therefore, the improved adsorption performance at the 5:1 ratio suggests that activated carbon and fly ash play complementary roles in the composite adsorbent. Activated carbon provides a high specific surface area and a well-developed pore structure, whereas fly ash contributes its mineral components. The combination of these complementary characteristics produced a composite adsorbent with superior adsorption performance compared with either material used individually, as illustrated in Figure 4. However, when fly ash was used as the sole adsorbent (FA:CC-AC ratio of 6:0), the adsorption capacity decreased to 0.26 mg/g with a removal efficiency of 64.65%. This reduction

indicates that fly ash alone exhibits a lower adsorption performance than the composite adsorbent. This finding is consistent with the BET results, which showed that fly ash possesses a substantially lower specific surface area than activated carbon. Although EDS analysis confirmed an increase in the Si and Al contents after calcination, the mineral composition alone was insufficient to compensate for the limited surface area and pore structure of fly ash when used individually. Therefore, the enhanced adsorption performance observed at the optimum FA:CC-AC ratio of 5:1 can be attributed to the complementary characteristics of activated carbon and fly ash rather than to the individual contribution of either material alone.

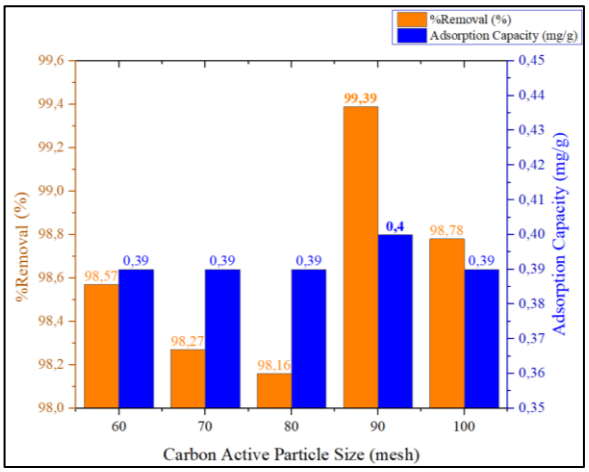


Figure 5. Adsorption capacity and % removal of methylene blue at varying activated carbon particle sizes

The effect of activated carbon particle size on methylene blue adsorption capacity and removal efficiency is presented in Figure 5. The results show that the 90 mesh particle size exhibited the highest adsorption performance, with an adsorption capacity of 0.40 mg/g and a removal efficiency of 99.39%. This value was higher than those obtained for 60–80 mesh (98.16–98.57%) and 100 mesh (98.78%). The improvement in adsorption performance from 60 to 90 mesh can be attributed to the increased contact area between adsorbent and adsorbate, as well as the shorter diffusion pathway for methylene blue molecules to reach the available adsorption sites (Musthofa et al., 2023).

This enhanced adsorption performance is also associated with the structural characteristics of KOH-activated corncob carbon. Based on BET analysis, KOH activation increased the surface area of corncob activated carbon from 8.80 to 40.88 m^2/g, indicating the development of a more accessible porous structure and an increase in available adsorption sites. Therefore, reducing particle size up to 90 mesh facilitates the accessibility of methylene blue molecules toward the developed pore structure, resulting in improved adsorption performance.

However, further reduction of particle size to 100 mesh did not provide additional improvement in adsorption efficiency. Excessive particle size reduction may increase surface energy and promote particle agglomeration due to stronger Van der Waals interactions between particles (Mashabi, 2017). This phenomenon can decrease the effective surface area and limit the accessibility of adsorption sites for methylene blue molecules. Therefore, 90 mesh can be considered the optimum particle size, providing a balance between increased surface contact and prevention of excessive particle aggregation. SEM-EDS characterization further supports the adsorbent characteristics by revealing an irregular carbonaceous surface morphology and the presence of carbon and oxygen elements, which may contribute to the adsorption interaction with methylene blue.

Beyond textural characteristics, the adsorption of MB is also governed by electrostatic and chemical interactions between the adsorbate and the adsorbent surface. As a cationic dye, MB carries a net positive charge in aqueous solution across a wide pH range. Under the near-neutral pH condition of the MB wastewater used in this study (pH ≈ 7), the adsorbent surface enriched with oxygen-containing functional groups (e.g., carboxyl and hydroxyl) generated during KOH activation, together with the negatively charged aluminosilicate surface of the fly ash component is expected to carry a net negative charge. This favors strong electrostatic attraction toward the cationic MB molecule. In addition, the graphitic domains present on the activated carbon surface may facilitate π–π stacking interactions with the aromatic ring system of MB, further contributing to the high removal efficiency observed. This combination of electrostatic attraction and possible π–π interaction is consistent with mechanisms commonly reported for MB adsorption onto carbon-based adsorbents (Aritonang et al., 2025).

Batch Adsorption of Cadmium(II) (Cd^{2+})

In the batch adsorption of Cd^{2+}, the experiment was conducted using the optimum operating conditions obtained from the MB adsorption results. The Cd^{2+} adsorption results shown in Figure 6 indicate a removal efficiency of 99.56% with an adsorption capacity of 1.659 mg/g.

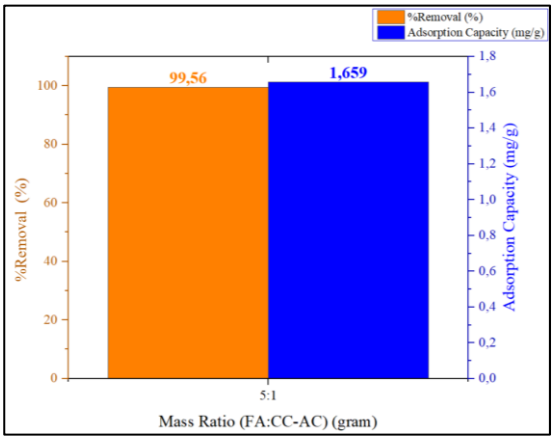


Figure 6. Adsorption capacity and % removal of Cd^{2+} under the optimum batch methylene blue operating conditions

The high removal efficiency indicates that the composite adsorbent, consisting of coal fly ash and 1 M KOH-activated corncob carbon at a ratio of 5 FA:1 CC-AC, exhibits a strong adsorption capability toward Cd^{2+} ions. The optimum conditions obtained from MB adsorption also provided favorable conditions for Cd^{2+} removal, indicating that the composite adsorbent possesses sufficient active sites for interacting with positively charged species. Although MB is a cationic dye and Cd^{2+} is a divalent metal ion, both adsorbates can interact with the functional groups and negatively charged sites available on the adsorbent surface.

The high Cd^{2+} removal performance can be attributed to the combined contribution of activated carbon and coal fly ash. The porous structure of activated carbon enhances the accessibility of Cd^{2+} ions to adsorption sites, while the aluminosilicate minerals present in coal fly ash provide additional sites for metal ion uptake. BET analysis of the activated carbon component showed an increase in surface area from 8.80 to 40.88 m^2/g after KOH activation, indicating the development of a more accessible porous structure that supports adsorption processes. Furthermore, SEM-EDS characterization revealed a heterogeneous surface morphology and the presence of carbon, oxygen, and mineral elements, which may contribute to Cd^{2+} interaction with the adsorbent surface (F. Chen et al., 2022).

The adsorption of Cd^{2+} is proposed to occur through several mechanisms, including electrostatic attraction, ion exchange, and surface complexation. These mechanisms have been reported as important pathways for Cd^{2+} removal using biochar- and fly ash-based adsorbents, with the contribution of each mechanism depending on the adsorbent characteristics and operating conditions (Qiu et al., 2022; Zhao et al., 2021). Although the obtained adsorption capacity was 1.659 mg/g, the removal efficiency reached 99.56%, indicating that the applied operating conditions were effective in reducing Cd^{2+} concentration from the solution.

Batch Adsorption of Cr(VI)

The composite's adsorption performance toward Cr(VI) under the optimum MB operating conditions (FA:CC-AC ratio of 5:1; 90 mesh) is shown in Figure 7. It should be noted that the initial concentrations differed across the three pollutants, synthetic MB solutions were prepared at 25 ppm and Cd^{2+} solutions were prepared at 100 ppm, whereas the real Cr(VI) wastewater (100× diluted) had a substantially higher initial concentration of 407.51 ppm. Consequently, direct comparison of adsorption capacities (qe) across pollutants should be interpreted with caution, as qe scales with the mass of adsorbate available in solution. The comparison across pollutants in this study is therefore more appropriately made on the basis of % removal, which reflects the adsorbent's relative affinity independent of initial concentration.

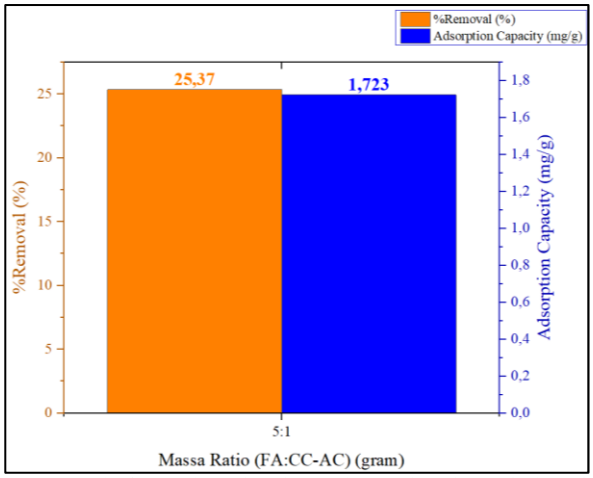


Figure 7. Adsorption capacity and % removal of Cr(VI) under the optimum batch methylene blue operating conditions

Unlike MB and Cd^{2+}, Cr(VI) adsorption performance was considerably lower, with an adsorption capacity of 1.7228 mg/g and only 25.37% removal. This result shows that the optimum operating conditions for one type of wastewater cannot be assumed to be optimum for wastewater with different chemical characteristics, even when using the same composite adsorbent.

This difference in performance is related to the chemical properties of the pollutants involved. MB and Cd^{2+} are cationic species that readily adsorb onto negatively charged surfaces, whereas Cr(VI) in aqueous solution exists as oxyanion species (CrO_4^{2-}, $Cr_2O_7^{2-}$, $HCrO_4^-$) whose proportions depend on pH (Sebabi et al., 2024). Sebabi et al. reported that the point of zero charge (pHpzc) of fly ash is around pH 3.62, while the pH of the Cr(VI) wastewater used in this study was 4.00, just above this pHpzc value. This means the composite surface, dominated by fly ash, remained negatively charged and generated electrostatic repulsion toward the anionic Cr(VI) species (Doke & Khan, 2017). Chen et al. reported a decrease in Cr(VI) % removal by activated carbon from around 40% at pH 3 to less than 1% at pH 10, consistent with the low Cr(VI) removal obtained in this study.

Beyond electrostatic repulsion, the non-zero Cr(VI) removal observed (25.37%) suggests that a secondary mechanism may also be operating. Carbonaceous surfaces bearing oxygen-containing functional groups are capable of reducing Cr(VI) to the less toxic Cr(III), which is subsequently retained on the adsorbent through electrostatic attraction or complexation, since Cr(III) carries a positive charge under the tested pH condition. Chen et al. demonstrated that powdered activated carbon can drive this reduction pathway, particularly under acidic conditions similar to those used in this study (pH 4.00). The corn cob-derived carbon component of the composite, which retained a relatively high carbon content (97.63%, Table 1) and a developed pore structure after KOH activation, may therefore have contributed a modest reductive capacity that partially offset the repulsion from the fly ash-dominated surface, while the fly ash component itself, being electrostatically unfavorable toward Cr(VI) at the tested pH, remained the dominant limiting factor. This proposed dual-mechanism interpretation would need to be confirmed through post-adsorption XPS or FTIR analysis of the Cr(VI)-loaded composite, which is recommended for future work to resolve the relative contribution of electrostatic repulsion versus surface-mediated reduction.

Comparison with Previous Studies

Table 4 compares the removal performance of the FA–CC-AC composite developed in this study with previously reported adsorbents derived from similar precursors. The composite's performance toward MB and Cd^{2+} is comparable to or competitive with these earlier reports, whereas its performance toward Cr(VI) remains considerably lower, consistent with the electrostatic repulsion mechanism.

Table 4. Comparison of adsorption performance with previously reported adsorbents

Adsorbent	Target Pollutant	%Removal	Reference
Corn cob activated carbon (CC-AC)	MB	Up to 99.03%	(Aritonang et al., 2025)
KOH-activated CC-AC	Cr(VI)	Up to 99.45%	(Zegeye et al., 2025)
Fly ash (FA)	MB	Up to 97.1%	(Dinh et al., 2021)
FA-CC-AC composite this study	MB	99.39%	This study
FA-CC-AC composite this study	Cd^{2+}	99.56%	This study
FA-CC-AC composite this study	Cr(VI)	25.37%	This study

CONCLUSIONS

KOH activation increased the specific surface area of corn cob carbon from 8.80 to 40.88 m^2/g and raised its carbon content to 97.63%, while calcination increased the surface area of fly ash from 0.32 to 1.65 m^2/g without altering the particles's basic morphology, and increased its silica and alumina content by 1.76× and 3.2×, respectively (21.89% Si and 15.31% Al). In batch adsorption, the fly ash–activated carbon composite at a 5:1 mass ratio and 90 mesh particle size achieved the highest MB removal of 99.39%, with an adsorption capacity of 0.4 mg/g. Under the same operating conditions, Cd^{2+} adsorption achieved 99.56% removal with a capacity of 1.659 mg/g, while Cr(VI) adsorption achieved only 25.37% removal with a capacity of 1.7228 mg/g. The enhanced adsorption performance observed after KOH activation and fly ash calcination indicates that both treatments successfully improved the adsorption properties of the composite adsorbent. The relatively low Cr(VI) removal is primarily associated with electrostatic repulsion between the negatively charged adsorbent surface and the dominant Cr(VI) oxyanions, with a possible secondary contribution from surface-mediated reduction of Cr(VI) to Cr(III) by the carbon component. This interpretation is consistent with previous reports on activated carbon–fly ash composites. These results indicate that the composite is highly effective for removing cationic dyes and metals such as MB and Cd^{2+}, but requires further surface charge modification to be effective against anionic pollutants such as Cr(VI). Post-adsorption spectroscopic characterization (e.g., XPS, FTIR) is recommended to directly confirm the relative contributions of electrostatic repulsion and surface-mediated reduction.

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