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ORIGINAL ARTICLE

Microwave-Assisted Pyrolysis of Spent Coffee Grounds: Impacts of Residence Time on Biochar Properties and Methylene Blue Adsorption Potential

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ABSTRACT – Spent coffee grounds (SCG) is a globally abundant lignocellulosic biomass that poses significant disposal challenges. This study investigates the sustainable conversion of SCG into functional biochar via microwave-assisted pyrolysis and evaluates its potential as a low-cost adsorbent for methylene blue (MB) removal from aqueous solutions. SCG was pyrolyzed at microwave power of 720 W for 10, 20, and 30 minutes. The optimal biochar, produced at 20 minutes (SCGB/20), exhibiting the highest carbon content (66.94%) and a low H/C atomic ratio (0.55), indicating aromatization and carbonization of SCG biochar. Fourier Transform Infrared analysis confirmed the progressive removal of volatile organic compounds, while SEM analysis revealed the development of mesoporous structure favourable for adsorption. SCGB/20 biochar demonstrated promising MB removal efficiencies of up to 92.9 % at low initial MB concentration (25 and 50 mg/L). An adsorption capacity of 41.38 mg/g was obtained after 24 hours equilibrium time. Langmuir isotherm analysis (R^2 = 0.9106) indicated favorable monolayer adsorption (R_l = 0.0389–0.1395), while kinetic studies revealed that the adsorption follows a pseudo-second-order model (R^2 = 0.9964). The adsorption mechanism is primarily governed by chemisorption such as electron sharing or exchange between the aromatic structures of the biochar and MB molecules rather than oxygen-containing functional groups. Despite its relatively limited physical porosity, the aromatized surface of SCGB/20 provides an effective platform for dye adsorption.

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INTRODUCTION

Spent coffee grounds (SCG), a solid residues generated from coffee processing, contain various chemical compounds such as protein (13.7 mg/kg), lipids (10-20%), cellulose (9-15%), hemicellulose (37-39%), and lignin (24-33%) [1-2]. Globally, SCG is produced in massive quantities with global production estimated at 6 millions of tons per year [3]. The improper disposal of this waste in landfills poses environmental issues such as greenhouse gas emissions and potential leaching of chemical components such as fats, proteins,

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caffeine into the environment [1; 3] . Therefore, there is a need to transform SCG into value-added products, such as biochar, which not only addresses the waste disposal problem but also aligns with the UN Sustainable Development Goals (SDG) 12 (Responsible consumption and Production), supporting the circular economy and sustainable resource management.

The valorisation of SCG into high-value products, such as bio-oil for renewable energy [4-5], biochar and activated carbon [3; 6], has become a major focus in sustainable waste management research. SCG is particularly attractive as a precursor due to its high carbon content (47-56.1%) [1], which is essential for producing effective biochar or carbonaceous adsorbents [3]. Biochar, a highly desirable carbon-rich solid product derived from the thermal decomposition of biomass, offers a large surface area, porous structure, and abundant surface functional groups, making it an excellent candidate for pollutant adsorption [7].

Previous studies have successfully demonstrated the utilization of SCG-derived biochar and activated carbon for the removal of various contaminants, including heavy metals like arsenic, cadmium, copper, lead, and various organic dyes such as crystal violet, malachite green, methyl orange [6], further establishing its potential as a versatile adsorbent material. For example, in a recent study from [8], more than 95 % of lithium ion was successfully removed by SCG activated carbon produced from slow pyrolysis at temperature range of 300-600°C, achieving adsorption capacity in the range of 35-80 mg/g for lithium adsorption. Another study from Cho et al. [9] demonstrated that SCG activated carbon produced from CO_2-assisted co-pyrolysis (650°C) with nano ion(III) oxides showed good adsorption performance towards metals antimony (7.0 mg/g), cadmium (12.7 mg/g) and nickel (16.8 mg/g). Besides, iron-impregnated SCG biochar produced from conventional pyrolysis using muffle furnace at temperature 600 °C for residence time of 4 hr demonstrated high methylene blue removal efficiency (98.3 %) [10].

However, conventional pyrolysis methods that typically carried out in the temperature range of 400-800 °C often require long heating times and high energy input, thus limiting process efficiency. Microwave-assisted pyrolysis, on the other hand, offers a promising alternative due to its rapid and volumetric heating mechanism. Unlike conventional heating, which relies on conduction from external heat sources, microwave irradiation directly couples with the biomass matrix, enabling faster heating rates, reduced energy consumption, and more uniform thermal decomposition. As a result, microwave-driven carbonization can potentially yield biochar with enhanced physicochemical properties, making it an attractive approach for producing high-performance adsorbents [11].

Methylene blue is one of the most commonly used cationic dyes in the textile industry and is frequently employed as a model pollutant in adsorption studies due to its recalcitrant nature. The release of methylene blue-containing effluents into aquatic systems leads to severe ecological and health impacts, highlighting the urgent need for effective treatment methods [12]. Among the available technologies, adsorption is a widely recognized technique due to its simple, effective and economical approach for dye removal from wastewater [13]. Nonetheless, the reliance on commercial activated carbon in adsorption, which is costly and derived from non-renewable resources has prompted increasing interest in the exploration of alternative, low-cost, and sustainable adsorbents [6].

Therefore, in this study, the valorisation of SCG into biochar via microwave-assisted pyrolysis has emerged as a promising strategy. In this work, the influence of microwave-assisted pyrolysis residence time on physicochemical properties of SCG biochar including the biochar yield, elemental analysis, and surface morphology were studied. Subsequently, the optimal SCG biochar produced was subjected to methylene blue adsorption experiments to unveil its adsorptive potential towards methylene blue removal efficiency. This study aims to develop an efficient and sustainable approach for managing SCG while enabling effective methylene blue remediation from wastewater.

MATERIALS AND METHODOLOGY

Biochar Preparation

Spent coffee ground (SCG) was collected from a local coffee shop in Sibu, Malaysia. Collected SCG samples were oven-dried at 105°C for 24 hours and sieved to produce homogenized sized of 355 μm before microwave pyrolysis to prevent mold formation. A customized microwave-assisted pyrolysis reactor (Brand: SHARP, Model: R-T25KG(W)) with maximum microwave power (900W) was used in this study. 5 g of SCG were used in pyrolysis. Nitrogen gas flow at 100 mL min^{-1} was used as a carrier gas to ensure anoxic condition for the whole duration of the microwave-assisted pyrolysis. During microwave-assisted pyrolysis

of SCG, the microwave power of 720 W was used while the duration of heating was varied at 10, 20 and 30 minutes. The SCG biochar (SCGB) produced were naturally cooled to room temperature before weighting to determine the biochar yield using equation (1).

Yield of biochar (wt. %) = mass of solid biochar (g)/ mass of SCG used (g) x 100 % Equation (1)

Biochar Characterization

Ultimate analysis was performed using CHN analyzer (Perkin Elmer 2400 Series II). Percentages of elements C, H, N were obtained from the analysis, while O was obtained via subtraction (O = 100 – C – H – N). Brunauer-Emmet-Teller (BET) surface area, total pore volume and pore size were measured by N_2 adsorption and desorption using Mircometrics 3Flex. Approximately 0.5 g of biochar was used for the analysis. Prior to analysis, the sample was firstly degassed under vacuum conditions at 250^{o}C for 4 hours. The BET model was used to calculate the specific surface area and the Barrett-Joyner-Halenda (BJH) adsorption model for pore size and total pore volume. Fourier Transform Infrared Spectroscopy (FTIR) analyses were performed using Spectrum 100, Perkin Elmer. The samples were scanned at 4000-650 cm^{-1} wavenumber range via attenuated total reflectance (ATR) accessory. The surface morphologies of samples were scanned using scanning electron microscope (SU5000, Hitachi). The samples were coated with gold using ion sputter at 4 mA current for 3 minute and then scanned with accelerating voltage of 10 kV.

Adsorption Experiment

Stock solution of methylene blue (100 mg/L) was prepared using methylene blue powder (Brand: Bendosen, CAS: 61-73-4, Molar mass: 319.85 g/mol) and dissolved in distilled water. Methylene blue adsorption experiments were performed in conical flask containing 50 mL working solution. In isotherm study, 2 g/L of adsorbent SCGB was added to methylene blue solution in a 100 mL conical flask with a different initial concentration of methylene blue from 25, 50, and 100 mg/L. The equilibrium adsorption data for MB on SCGB were evaluated using Langmuir and Freundlich isotherm models. For the kinetic study of methylene blue adsorption, SCG biochar (2 g/L) was added into 50 mL methylene blue working solution (100 mg/L). The concentrations of methylene blue were determined at the time interval from 120 min to 1440 min. Two kinetic models: pseudo-first-order and pseudo-second-order kinetic were used to describe the adsorption process of MB onto SCGB. In adsorption experiments, the filtrates were collected through gravimetric filtration and analyzed using a UV-Vis spectrophotometer (Genesys 10s) at the wavelength of 665 nm [10]. Triplicates of the batch adsorption experiment were carried out to obtain the average experimental data. The removal percentage (%) and adsorption capacities (Q_e, mg/g) of biochar in all batch adsorption studies were calculated according to Equation (2) and Equation (3), where C_o denotes the initial concentration of methylene blue adsorbate (mg/L), C_e denotes the concentration of methylene blue at equilibrium (mg/L), V is the total volume of working solution (L) and m is the mass of adsorbent (g).

Removal percentage (%) = $(C_o – C_e)/ C_o$ x 100 % Equation (2)

Adsorption capacity, Q_e (mg/g) = $(C_o – C_e)$ x V/m Equation (3)

RESULTS AND DISCUSSION

Biochar Yield and Elemental analysis

Microwave-assisted pyrolysis showed a significant impact on the biochar yield. The solid yield of SCGB decreased from 38.1 % at 10 min to 27.8 % at 20 min and further decreased to 16.4 % at 30 min (Figure 1). Results showed that microwave pyrolysis time has strong influence on the yield of SCGB. The increase in microwave heating time from 10 to 30 minutes resulted in gradual reduction in biochar yield. This is attributed to the enhanced carbonization and progressive devolatilization of spent coffee grounds, leading to the release of non-condensable gases and volatile matters such as CO2, CO, H2 [7; 14]. In addition,

prolonged microwave heating exposure also promotes secondary cracking reactions, further converting solid carbon into gaseous products, thereby reducing the biochar yield.

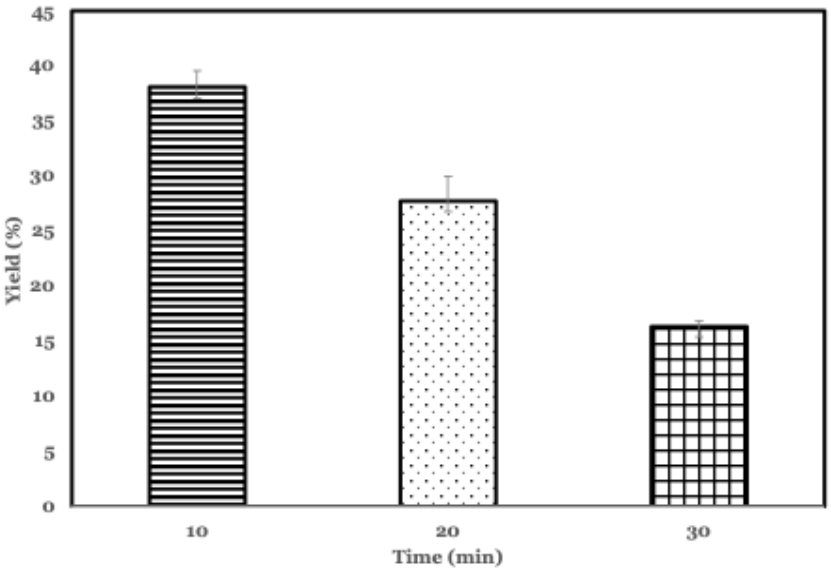

Figure 1. Spent coffee grounds biochar (SCGB) yield (%) at different reaction time

Figure 2 shows the elemental composition of SCGB prepared in this study. The elemental composition provide clear evidence of the thermochemical transformation occurring during microwave pyrolysis. The carbon content of untreated SCG is 48.87 %, close to the value of 52 % as reported in [14]. For SCG biochar, the carbon content was found to increase with pyrolysis time, while oxygen content decreased. The maximum carbon content of 66.94% was found in the SCG biochar produced at 20 min (SCGB/20). In contrast, the oxygen content of 26.96% was the lowest in SCGB/20. This trend is similar to the result reported in [15]. This finding demonstrated that oxygen-containing groups undergo degradation in the form of volatile compounds such as CO_2, CO or NO_x during prolonged microwave heating. While SCG biochar undergo degradation and decomposition, leading to a reduction in oxygen-functional groups, its aromaticity increased as evidenced by the decreasing H/C atomic ratio of SCG biochar at different microwave heating time from 10-30 min (Table 1). The decrease in H/C atomic ratio from 1.59 in raw SCG to 0.33 in SCGB/30 demonstrates the development of a more stable aromatic skeleton over heating time [16].

While extending the pyrolysis time to 30 minutes, SCGB/30 achieves the highest degree of carbonization and a lowest H/C ratio of 0.33, it results in a significant drop in solid yield to 16.4%. In contrast, the SCGB/20 produced at 20 minutes time represents a more strategic optimum where the material has already undergone substantial thermochemical transformation, reaching its peak carbon content of 66.94% and H/C atomic ratio of 0.55. The aromatic density achieved at this stage (H/C ratio of 0.55) could be sufficient to facilitate the chemical interactions needed for the removal of methylene blue. Furthermore, SCGB/20 offers a significantly higher solid recovery of 27.8% which is nearly double the yield of the 30-minute SCG biochar. This balance makes the 20-minute pyrolysis process more viable and efficient choice for practical applications, as it maximizes the production of a quality adsorbent from a fixed quantity of raw waste without the excessive material loss in prolonged microwave pyrolysis.

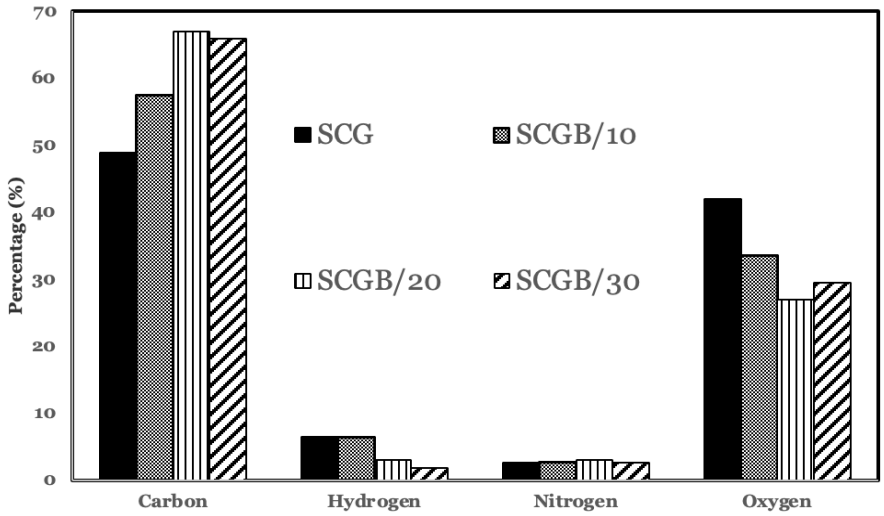

Figure 2. Elemental composition of spent coffee grounds biochar (SCGB) produced at different reaction time

Table 1. H/C and O/C ratio of spent coffee grounds biochar

Properties	SCG	SCGB/10	SCGB/20	SCGB/30
H/C	1.59	1.32	0.55	0.33
O/C	0.65	0.44	0.30	0.34

Surface morphology of SCG and SCG Biochar

FTIR spectra of raw SCG and SCG biochar produced at different reaction holding time were shown in Figure 3. Two pronounced peaks at 2925 and 2853 cm^{-1} were observed in raw SCG, which attributed to the C-H stretch vibrations for methyl and methylene groups inherited from the presence of caffeine and lipids in coffee grounds [17-18]. The peaks near 1708 cm^{-1} and 1056 cm^{-1} were associated with the carbonyl C=O and C-O stretching attributed to cellulose, hemicellulose and lignin in SCG [18-19]. These oxygenated functional groups vanished in SCGB/30 but still slightly present in SGB/20, indicating the decomposition of organic compounds during prolonged microwave heating. Besides, at a pyrolysis time of 20 min, SCGB/20 biochar shows a peak increase near 1363 cm^{-1}, representing aromatic C-C stretching peak [20] and the formation of a more carbonized, aromatic surface. This aromatized surface potentially provides an alternative chemical platform for MB dye adsorption through $\pi - \pi$ interactions between the aromatic rings of the biochar and the dye molecules [21]. As this aromatic peak decreases by 30 min, a pyrolysis time of 20 min is considered optimal, it maximizes the aromatic density required for chemical adsorption, that effectively compensating for the material's limited physical porosity as discussed in the next section. Therefore, a pyrolysis time of 20 min was identified as optimal for SCG biochar production and this sample, SCGB/20 was selected for all subsequent adsorption experiments.

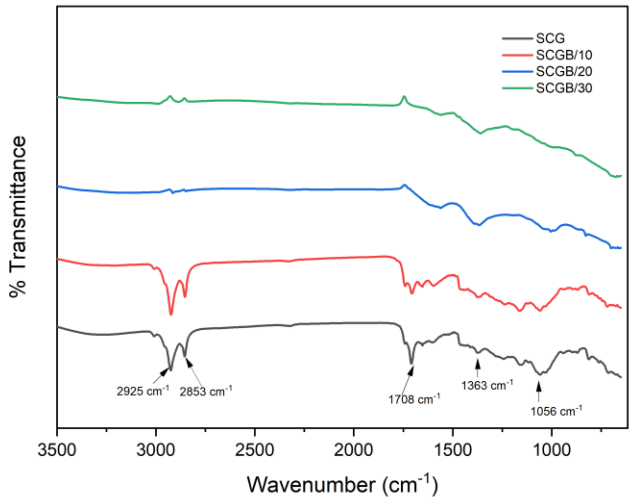

Figure 3. FTIR spectra of raw SCG and SCG biochar produced at different residence time (10, 20, 30 minutes)

The visual transformation of SCG before and after microwave pyrolysis at 20 minutes was shown in Figure 4. Raw SCG (Figure 4a) appears as a brown and granular structure, typical of organic-rich biomass. After pyrolysis, the resulting SCG biochar (SCGB/20) turns blackish colour (Figure 4b). The distinct colour change from brown to black reflects the thermal decomposition of SCG to a carbon-rich structure during the pyrolysis process. Besides, quantitative analysis via BET method reveals that SCGB/20 has a low specific surface area of 0.7330 m^2/g and a total pore volume of 0.002266 cm^3/g (Table 2). In addition, based on the desorption data, the average pore diameter of SCGB/20 is 21.92 nm, indicating that SCGB/20 biochar is a mesoporous biochar as its pore size falls within the range of 2 -50 nm. The visual data (Figure 5) obtained from Scanning Electron Microscopy (SEM) corroborates these findings. At a magnification of 500x, SCGB/20 biochar displays a honeycomb-like porous structure. The lack of surface texture or pitting on the smooth pore walls aligns with the low specific surface area measured by BET. While the low specific surface area of SCGB/20 might potentially limiting the physical adsorption capacity for MB. The adsorption of MB in SCGB/20 is therefore likely facilitated by strong chemical interactions, which is strongly supported by the best-fit to the pseudo-second-order kinetic model as discussed in the next section.

(a) (b)

Figure 4. (a) Spent coffee grounds and (b) spent coffee grounds biochar (SCGB/20)

Table 2: BET analysis of SCGB/20

BET Surface Area	0.7330 m^2/g
Total Pore Volume	0.002266 cm^3/g
Average Pore Diameter	21.92 nm

(a) (b)

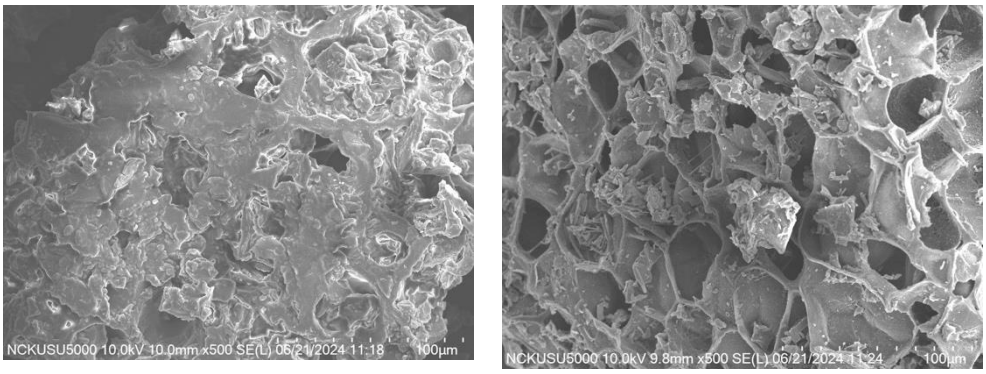

Figure 5. SEM micrographs of (a) raw SCG and (b) SCG biochar (SCGB/20)

Adsorption Performance on Methylene Blue

In this study, SCGB/20 was used in the MB adsorption experiments to evaluate its efficacy towards MB removal. The adsorption experimental conditions such as SCGB/20 adsorbent dosage (2 g/L) and adsorbent contact time (2 hours) were remained constant throughout the adsorption experiment. The adsorption experiment in this study was carried out at 2 hours based on previous study by Jayaraman et al., [22], which proven that equilibrium of MB dye adsorption was achieved within 60 minutes. Figure 6 illustrates the obvious colour change observed after adsorption tests. The colour of solutions changed from dark blue before adsorption to a much lighter blue solution after adsorption across different initial MB concentrations (25, 50 100 mg/L). This indicates that most of the recalcitrant MB were successfully removed or adsorbed, demonstrating that SCGB/20 exhibited high affinity and provides sufficient actives sites to adsorb MB dye.

Correspondingly, Figure 7 shows the MB removal percentage and adsorption capacity of SCGB/20. In comparison, SCGB/20 showed better MB removal performance at lower initial MB concentrations (25 and 50 mg/L), where the removal percentage of 92.9 % were achieved at these concentrations. However, when the initial MB concentration increased to 100 mg/L, the MB removal percentage dropped significantly to 62.5 %. This decline could be due to saturation of available adsorption sites on SCG biochar, leading to a decrease in removal percentage as the initial concentration of MB increases. Besides, the equilibrium adsorption capacity for MB increased with increasing initial concentration. In this study, the experimental equilibrium concentration of MB is 30.19 mg/g at an initial concentration of 100 mg/L.

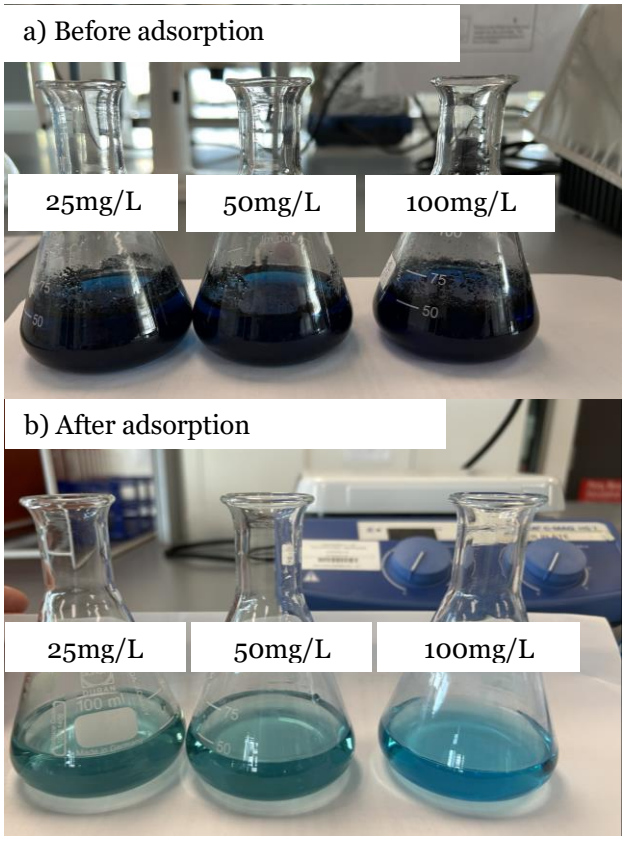

Figure 6. Visual comparison of methylene blue solutions before and after adsorption by SCGB/20 biochar at different initial concentrations (25, 50, 100 mg/L)

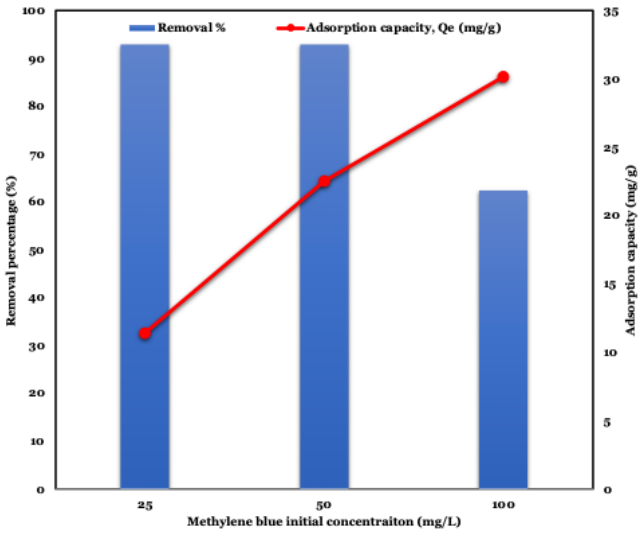

Figure 7. Methylene blue removal percentage and adsorption capacity of spent coffee ground biochar. Adsorption conditions: biochar dosage = 2g/L, contact time = 2 hrs, temperature = 25°C

In the present study, two isotherm models which is Langmuir isotherm and Freundlich isotherm were used to evaluate how the adsorbed MB molecules are distributed between the liquid and solid phase at equilibrium. Mathematically, the Langmuir isotherm is expressed by the equation (4).

$$\frac{1}{Q_e} = \left(\frac{1}{K_L Q_m}\right)\frac{1}{C_e} + \frac{1}{Q_m} \qquad \text{equation (4)}$$

First, the isotherm Langmuir model explains the quantitative information of monolayer adsorption on the homogenous surface of adsorbent. In this study, the Q_e(mg/g) represents the quantity of MB that has been adsorbed at the point of equilibrium. Q_m(mg/g) denotes the maximum adsorption capacity of the SCGB adsorbent to adsorb MB. K_l (L/mg) is the equilibrium constant to determine the overall adsorption process. Lastly, C_e(mg/L) represents the equilibrium concentration of MB in the aqueous phase.

For Freundlich isotherm, it describes the adsorption performance of adsorbate occurring on heterogenous surface. The Freundlich isotherm is expressed by the equation (5). The parameter Q_e(mg/g) is the amount of adsorbed mass per unit of the adsorbent when equilibrium is reached. C_e(mg/L) is denoted as the equilibrium concentration of MB in aqueous phase. K_F and $\frac{1}{n}$ are also essential as they denote the adsorption capacity and intensity, respectively.

$$\log Q_e = \log K_F + \frac{1}{n}\log C_e \qquad \text{equation (5)}$$

Comparing the two models, the Langmuir model ($R^2 = 0.9106$) provides a better fit for the MB adsorption on SCB biochar than the Freundlich model ($R^2 = 0.7400$) (Figure 8). This statistical result shows that the adsorption process primarily involves monolayer coverage on SCG biochar surface with the availability of adsorption sites as the rate-limiting factor [23]. This finding was similar to a reported study on the adsorption of MB by activated coffee husk hydrochar [24]. Besides, the Langmuir separation factor, $R_L$is used to determine if the adsorption process is favorable. The adsorption process is favorable if $0 < R_L < 1$, unfavorable if $R_L > 1$, and regarded as linear and irreversible if R_l equals to 1 and 0, respectively [23]. The calculated separation factors are in the range of 0.0389-0.1395 for all concentrations confirm that the adsorption process is highly favorable (Table 3). Generally, SCG biochar can act as an effective adsorbent for removing MB dyes. However, once the available adsorption sites on the SCG biochar surface become occupied, the removal percentage decreases due to limited number of remaining available active sites for further adsorption.

In addition, the adsorption rate and adsorption mechanism of MB dyes by SCG biochar was evaluated using pseudo-first-order and pseudo-second order kinetic models. Pseudo-first-order kinetic model predicts the adsorption mechanism between the dye adsorbate and adsorbent based on the adsorbent capacity, while pseudo-second-order kinetic model predicts the chemisorption mechanism over time until reaching equilibrium state. Mathematically, the pseudo-first-order and pseudo-second-order kinetic models are expressed by the equation (6) & (7), respectively. Q_e (mg/g) represents the adsorption capacity at equilibrium, Q_t (mg/g) is the adsorption capacity at time t, k_1 is the pseudo-first-oder rate constant (min^{-1}), k_2 is the pseudo-second-oder rate constant (g mg^{-1} min^{-1}).

$$\ln(Q_e - Q_t) = \ln Q_e - k_1 t \qquad \text{equation (6)}$$

$$\frac{t}{Q_t} = \frac{1}{(k_2 {Q_e}^2) + \left(\frac{1}{Q_e}\right)t} \qquad \text{equation (7)}$$

As shown in Table 3, the adsorption of MB at initial concentration of 100 mg/L showed the best fit to the pseudo-second-order with $R^2 = 0.9964$. This strong correlation demonstrates that pseudo-second-order kinetic model adequately describes the adsorption of MB onto SCG biochar is predominantly governed by chemisorption. Besides, the value of the adsorption capacity, Q_e was derived from the slope of the pseudo-second-order plot. Based on pseudo-second-order kinetic model, the calculated maximum adsorption capacity of MB is 42.37 mg/g and is very close to the experimental adsorption capacity which is 41.38 mg/g. This further confirms that MB adsorption onto SCG biochar involves chemisorption mechanism such as electron sharing or exchange between the MB adsorbate and adsorbent surface.

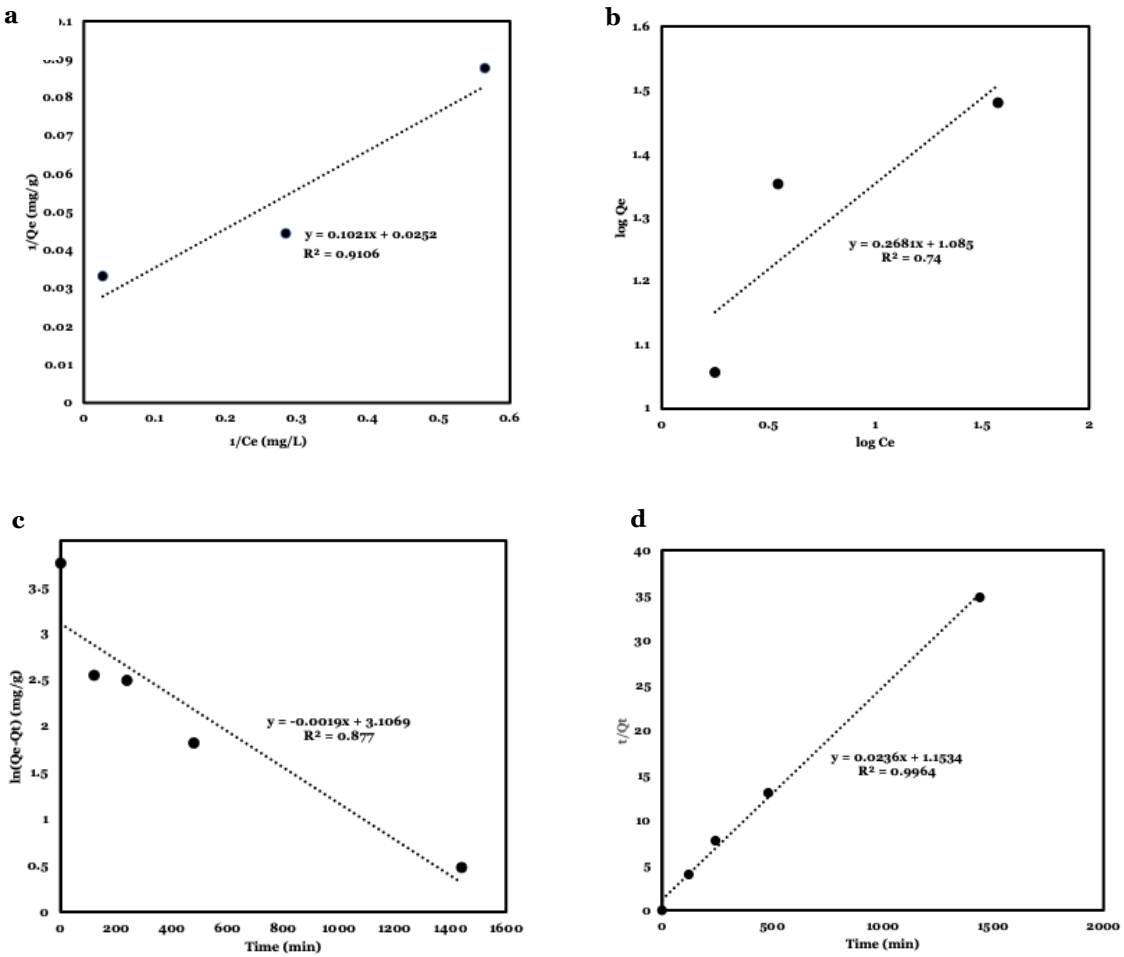

Figure 8. Methylene blue adsorption by SCG biochar modelled using (a) Langmuir isotherm, (b) Freundlich isotherm, (c) pseudo-first-order kinetic, (d) pseudo-second-order kinetic.

Table 3. Summary of isotherm and kinetic parameters of methylene blue adsorption

Isotherm model	Model parameters	SCGB/20
Langmuir	Langmuir maximum adsorption capacity, Q_m (mg/g)	39.6825
	Langmuir constant, K_L (L/mg)	0.2468
	Determination coefficient, R^2	0.9106
	Separation factor, R_L	0.0389-0.1395
Freundlich	Capacity factor, K_F	12.1619
	Freundlich intensity, n	3.7299
	Determination coefficient, R^2	0.7400
Pseudo first order	$Q_{e,cal}$ (mg/g)	22.3527
	Rate constant, k_1 (min^{-1})	0.0019

	R^2	0.8770
Pseudo second order	$Q_{e,cal}$ (mg/g)	42.3700
	Rate constant, k_2 (g mg^{-1} min^{-1})	0.0005
	R^2	0.9964
	$Q_{e,exp}$ (mg/g)	41.3842

Comparison of Adsorption Efficiency of Spent Coffee Ground Biochar with Literature

Table 4 presents a comparative analysis of the methylene blue adsorption performance of the SCGB/20 biochar prepared in this study versus activated SCG reported in literatures. SCGB/20 demonstrated a maximum adsorption capacity of 41.38 mg/g with a removal efficiency of 83.29% after 24 hours. In contrast, chemically-activated SCG via conventional pyrolysis, achieved significantly higher adsorption capacities (up to 179 mg/g).This performance gap is primarily attributed to the structural differences between pristine biochar and activated carbon. As illustrated in the comparison above, chemical or physical activation processes dramatically increase specific surface area and micropore volume, providing more active sites for methylene blue dye binding. SCGB/20, that relying on simple microwave-assisted pyrolysis, likely possesses a less developed pore structure, resulting in lower MB removal efficiency.

However, a direct comparison of removal efficiency must account for the initial pollutant load. This study evaluated SCGB/20 at a high initial MB concentration of 100 mg/L, simulating high-strength industrial wastewater. Conversely, the literature references operated at much lower concentrations (10.2–20 mg/L), where achieving near 100% removal is kinetically less demanding. Although SCGB/20 exhibits lower adsorption capacity than the activated SCG, SCGB/20 demonstrates robust performance for bulk contaminant removal without the need for the costly and chemically intensive activation steps required for high-performance adsorbent. Besides, the sustainable and fast biochar production technique via microwave heating, together with the low-cost and abundantly available SCG feedstock and its potential for performance enhancement make spent coffee grounds derived biochar a promising candidate for future development as a green adsorbent in wastewater treatment.

Table 4. Comparison of methylene blue adsorption performance of spent coffee ground (SCG) biochar with SCG activated carbon

Initial concentration (mg/L)	Feedstock and preparation method	Adsorbent dosage (g/L)	Adsorption time (hr)	MB removal percentage (%)	MB adsorption capacity (mg/g)	Ref.
100	SCG biochar (microwave pyrolysis, 20 min)	2	2	62.47	30.19	In this study
100	SCG biochar (microwave pyrolysis, 20 min)	2	24	83.29	41.38	In this study
20	KOH-activated SCG	0.5	-	100	179	[25]
10.2	Fe-activated SCG	0.5	1	98.3	-	[10]
200	KOH-urea-activated SCG	0.3	3	-	499.9	[26]

30	SCG-biochar (slow pyrolysis)	20	3	99.99	-	[27]

CONCLUSION

This study successfully demonstrated the sustainable conversion of spent coffee grounds (SCG) into functional biochar via microwave-assisted pyrolysis. A 20 minute microwave pyrolysis of SCG optimally balances carbonization (66.94 % carbon), creating a mesoporous, volatile-free biochar structure (H/C atomic ratio 0.55) that facilitates the adsorption of methylene blue dye. FTIR analysis evidenced the removal of volatile organic compounds and progressive aromatization of SCG biochar with prolonged heating time. SCG biochar produced at 20 min (SCGB/20) showed promising adsorption performance toward methylene blue (MB), achieving removal efficiencies of up to 92.9% at low initial dye concentrations (25-50mg/L), and an experimental adsorption capacity of 41.38 mg/g after 24 hours. Although the adsorption efficiency was lower than that of activated SCG, SCG biochar demonstrated potential as a low-cost, readily-available, and greener adsorbent. Langmuir isotherm analysis (R^2 = 0.9106) indicated that methylene blue adsorption onto SCG biochar occurs via favourable monolayer adsorption (R_L = 0.0389–0.1395), demonstrating its effectiveness as an adsorbent. Kinetic studies indicated that the adsorption process follows the pseudo-second-order model (R^2= 0.9964), suggesting that the mechanism is not primarily governed by oxygen-containing functional groups, but rather by chemical interaction between the aromatic structures of the biochar and MB molecules. Even in the absence of a highly developed porous structure or abundant surface functional groups, the aromatized surface of SCGB/20 provides an effective platform for MB dye adsorption, thereby compensating for its limited physical porosity. Overall, this findings showed that microwave-assisted pyrolysis is a rapid and viable approach for valorising spent coffee grounds into functional adsorbents. Future work should focus on surface activation or microwave parameter optimization such as temperature controlling to enhance adsorption performance and broaden the applicability of SCG-derived biochar in wastewater treatment.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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