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Co-Pyrolysis of Cassava Peel and Sheep Manure Through Fixed-Bed Pyrolytic Unit for Biochar Application

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Abstract

The pyrolysis of agricultural and livestock residues through thermochemical conversion offers a sustainable pathway for waste management and biochar production. This study investigates the co-pyrolysis of cassava peel (CP) and sheep manure (SM) for biochar yield optimization using a fixed-bed pyrolytic reactor. A central composite design (CCD) under response surface methodology was employed to evaluate the effects of pyrolysis temperature (237.87–662.13 °C) and residence time (26.89–48.10 min) on biochar yield for three feedstock ratios: CP/SM (0/100), CP/SM (100/0), and CP/SM (50/50). The physicochemical characterization of the biomass through proximate and ultimate analyses confirmed their suitability for thermochemical conversion. Quadratic models were developed to describe the relationship between process parameters and biochar yield. The statistical evaluation using analysis of variance indicated that the developed models were highly significant ($p < 0.0001$) with strong predictive capability, yielding coefficients of determination (R^2) of 0.9924, 0.9797, and 0.9863 for CP/SM (0/100), CP/SM (100/0), and CP/SM (50/50), respectively. Among the operating parameters, pyrolysis temperature was identified as the most influential factor affecting biochar yield, whereas residence time exhibited a comparatively minor effect. The experimental results revealed that sheep manure produced higher biochar yields due to its higher fixed carbon and ash content, while cassava peel generated relatively lower yields because of its elevated volatile matter fraction. The co-pyrolysis of CP and SM (50/50) demonstrated stable char yields, suggesting beneficial interactions between the two feedstocks. The findings highlight the potential of integrating agricultural residues and animal manure through co-pyrolysis for sustainable biochar production and efficient biomass waste management.

Keywords: *Optimization, pyrolysis, biochar, sheep manure, cassava peel, volatile matter.*

1.0 Introduction

Increasing concerns surrounding climate change, energy security, and economic resilience have accelerated global interest in re-evaluating traditional energy supply structures and adopting alternative technologies (Jameel et al., 2024). Biomass conversion has emerged as a viable pathway, where mechanical, biological, physical, and thermochemical processes support the production of sustainable biofuels and value-added bioproducts, which significantly reduce environmental impact compared to conventional fossil-based systems (Oladosu et al., 2027). Biomass valorization aligns with low-carbon and circular economy principles and directly supports Sustainable Development Goals (SDGs) associated with clean energy access, responsible production and consumption, technological innovation, and climate action (Kobayashi & Nakajima, 2021). Biowaste-to-bioenergy technologies accounted for USD 116.5 billion in market value in 2021 and are projected to reach USD 229 billion by 2030, reflecting the growing economic relevance of biomass conversion (Hoyos-Sebá et al., 2024).

Agricultural residues, woods, and municipal solid waste constitute readily available feedstocks; however, pretreatment is typically necessary to optimize conversion efficiency and product characteristics (Fermanelli et al., 2020). Agricultural operations generate diverse residues, including manure, crop remnants, and processing waste, containing lignocellulosic and nutrient-rich components that are suitable for energy recovery (Afraz et al., 2024). Cow dung is the most investigated manure for bioenergy applications; other underutilized manures (such as sheep manure) present unique advantages (Matheos et al., 2024). Sheep manure contains lower lignin content relative to other livestock residues, which supports improved thermal decomposition and enhances the potential for higher biochar yields under pyrolytic conditions (Matheos et al., 2024). Moreover, sheep population growth across sub-Saharan Africa continues to expand (Ernest & Yakub, 2024), resulting in increasing quantities of manure that are often poorly managed or left unexploited, contributing to methane emissions and nutrient runoff. Similarly, cassava residues represent a strategically relevant biomass source in Nigeria and many regions of sub-Saharan Africa, where cassava is a staple crop with annual production generating significant volumes of peels, stalks, and processing effluents (Ernest &

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Yakub, 2024). These residues are commonly discarded, openly burned, or inadequately disposed of, leading to environmental pollution and lost bioenergy opportunities. Their carbohydrate-rich composition and high volatile matter content make cassava residues suitable for thermochemical conversion and promising candidates for biochar production (Egbosiuba, 2022).

Thermochemical conversion (particularly pyrolysis) has demonstrated considerable promise for producing biochar, bio-oil, and syngas from a wide variety of biomass feedstocks (Yang et al., 2021). Pyrolysis is a thermochemical conversion process in which biomass is heated in the absence of oxygen, typically between 300–700 °C, resulting in the production of biochar (solid), bio-oil (liquid), and syngas (gas) (Güleç et al., 2022). Product distribution depends on key operational parameters such as temperature, heating rate, and residence time (de Almeida et al., 2022). Slow pyrolysis favors biochar production, while fast pyrolysis maximizes bio-oil yield (Mohammed et al., 2016). As a sustainable conversion pathway, pyrolysis enables the efficient utilization of lignocellulosic residues and agricultural wastes, reducing open burning and associated emissions. The biochar fraction contributes to long-term carbon sequestration due to its stable aromatic structure, while syngas can be recycled to supply process heat, enhancing the energy efficiency (Hoang et al., 2021).

Recent studies have explored the use of cassava residues and animal manure as low-cost feedstocks for biochar production, demonstrating enhanced soil amendment properties and improved nutrient retention. Biochar produced from these wastes not only facilitates long-term carbon sequestration due to its stable aromatic structure but also enhances the removal of contaminants, soil fertility, water-holding capacity, and microbial activity, supporting sustainable agricultural productivity while mitigating greenhouse gas emissions (Odeyemi et al., 2023; Xie et al., 2024). Siswantara et al. (2026) examined the energy performance of sheep manure pyrolysis conducted in a fixed-bed reactor system. An energy balance analysis was employed to assess process efficiency under varying operating conditions, with the optimal parameter range resulting in a maximum biochar yield of 72.4%. Odeyemi et al. (2023) valorized waste cassava peel into biochar with a specific surface area (SSA) of 319.784 m^2/g using a top-lit updraft reactor with retort heating. In another study, Xie et al. (2024) converted sheep manure to biochar for the adsorption of U(VI). However, the biochar derived from sheep manure has high content of ash, which can reduce the adsorption efficiency. Through co-pyrolysis of poultry litter, swine manure, and selected industrial residues, (Rodriguez et al., 2021) produced ten distinct biochars under varying thermal conditions. Increasing the process temperature decreased yield and volatile fractions but enhanced ash content, carbon stability, CEC, and mineral accumulation. The combined feedstocks exhibited beneficial interactions that strengthened soil amendment properties such as water-holding capacity, buffering ability, and nutrient concentration. Despite the potential of co-pyrolysis as a sustainable waste valorization strategy, the synergistic interactions between sheep manure and cassava peel influencing biochar yield, pore development, and surface chemistry remain underexplored.

The co-pyrolysis of cassava peel (CP) and sheep manure (SM) is justified by their complementary physicochemical characteristics. Cassava peel is carbon-rich but relatively low in nitrogen and ash, whereas sheep manure contains higher mineral content and nitrogenous compounds (Awasthi et al., 2020; Hamissou et al., 2023). Their synergistic interaction during co-pyrolysis can enhance biochar yield, improve nutrient content (particularly N, P, and K), and increase surface functionality. Additionally, mineral species in manure may catalyze thermal decomposition, promoting pore development and improving biochar stability and agronomic value. This integrated valorization approach also addresses simultaneous management of agro-industrial and livestock wastes, supporting circular bioeconomy and sustainable soil restoration strategies (Silva et al., 2026).

Therefore, this study aims to investigate the biochar yield from copyrolysis of cassava residues and sheep manure using a fixed-bed pyrolytic unit and correlate to how feedstock characteristics and process parameters influence biochar production. This study contributes to the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), through the valorization of agricultural and livestock residues into value-added biochar via co-pyrolysis.

2.0 Materials and Methods

2.1 Collection and preparation of samples

Fresh CPs were obtained from local cassava processing facilities in Lafiagi, Kwara state, while SM was collected from nearby livestock farms in the same locality. Only uncontaminated peels and recently excreted manure were selected to minimize degradation and external impurities. The feedstocks were thoroughly washed with water to remove adhering soil and debris. Cassava peels were cut into small pieces (~2–3 cm) to facilitate uniform drying. Both cassava peel and sheep manure were oven-dried (as shown in Figure 1) at 80 °C

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until constant weight was achieved. The moisture content was subsequently determined using gravimetric method, and values below 10% were obtained, which is critical for efficient pyrolysis.

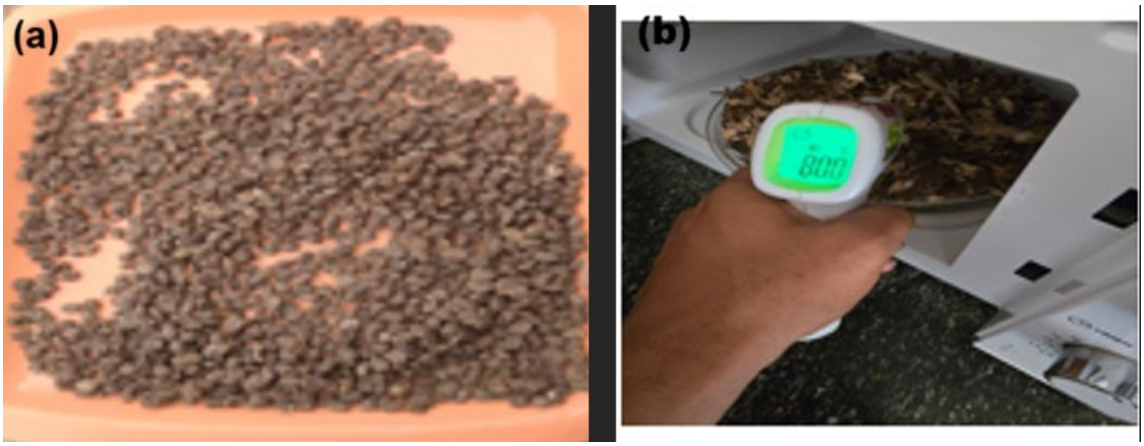

Figure 1. Oven-dried biomass feedstocks at 80 °C prior to pyrolysis : (a) cleaned sheep manure and (b) cleaned cassava peel during the drying process.

The dried samples were then ground to a particle size of 1–5 mm using a mechanical grinder to ensure homogeneity and consistent thermal decomposition. For co-pyrolysis experiments, CP and SM were mixed at ratios of 0/100, 100/0, and 50/50 and stored in airtight containers under dry conditions until further use. These proportions of the feedstocks are subjected to process conditions as obtained from the central composite design (CCD). This preparation ensured uniformity, enhanced feedstock reactivity, and reproducibility of pyrolysis outcomes.

2.2 Design of the experiment using the central composite design (CCD)

The CCD under the Response Surface Methodology (RSM) was employed for the design and optimization of the process parameters. The experimental design involved choosing the minimal set of design parameters and conducting a specific number of experimental trials to develop the most reliable regression models. CCD was adopted to efficiently develop a quadratic response model while minimizing the number of required experiments (Mohamed et al., 2014). Pyrolysis temperature and residence time were investigated at three coded levels (−1, 0, +1) (as presented in Table 1) using Design-Expert software (v7.1.5), which result to a total of 13 experimental runs.

Table 1. The three coded levels for the considered pyrolysis factors

Factor	Code	Unit	Low (−1)	Central (0)	High (+1)
Temperature	A	°C	237.87	450.00	662.13
Residence time	B	Minute	26.89	37.50	48.10

2.3 Proximate and ultimate analysis of biomass feedstocks

Proximate analysis of cassava peel and sheep manure was conducted to determine moisture content, volatile matter, ash content, and fixed carbon in accordance with standard procedures (ASTM E871, ASTM E872, and ASTM D3172). Samples were initially air-dried and then oven-dried at 105 °C to constant weight to determine moisture content (%MC) (Oladosu et al., 2021) using Equation 1.

$$\%MC = \frac{W_{\text{initial}} - W_{\text{dry}}}{W_{\text{initial}}} \times 100 \quad (1)$$

where $W_{\text{initial}}$is the wet sample mass and $W_{\text{dry}}$is the dry mass after oven drying.

Volatile matter (VM) was measured by placing oven-dried samples in a covered, inert crucible inside a muffle furnace at 950 ± 20 °C for 7 min (Oladosu et al., 2024). Weight loss after heating was used to calculate the VM fraction using Equation 2.

$$\%VM = \frac{W_{\text{dry}} - W_{\text{after VM}}}{W_{\text{dry}}} \times 100 \quad (2)$$

where $W_{\text{after VM}}$ represents the mass of the sample after volatile matter determination.

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For ash content, samples were combusted in a muffle furnace at 550 ± 25 °C for 4 h until constant weight. Ash content was calculated as provided in Equation 3.

$$\%\text{Ash} = \frac{W_{\text{ash}}}{W_{\text{dry}}} \times 100 \quad (3)$$

and fixed carbon (FC) was determined by difference using Equation 4.

$$\%\text{FC} = 100 - (\%\text{Moisture} + \%\text{VM} + \%\text{Ash}) \quad (4)$$

Ultimate analysis for elemental composition (C, H, N, S, and O) was carried out using a CHNS analyzer (e.g., PerkinElmer 2400 Series II) following manufacturer protocols. Oxygen content was calculated by difference (Singh et al., 2013) as stated in Equation 5.

$$\%\text{O} = 100 - (\%\text{C} + \%\text{H} + \%\text{N} + \%\text{S}) \quad (5)$$

Elemental results were used to derive the empirical formulas and assess biomass quality for thermochemical conversion (Jun et al., 2022). The higher heating value (HHV) was experimentally evaluated using a Parr 6100 oxygen bomb calorimeter under controlled conditions (Oladosu et al., 2024), adhering strictly to the procedures outlined in BS EN 14918 for the determination of gross calorific value of solid biofuels. All analyses were performed in triplicate.

2.4 Pyrolysis experimental setup

Pyrolysis experiments were conducted using a fixed-bed pyrolytic reactor (as shown in Figure 2). The reactor was placed inside an electrically heated tubular furnace equipped with a programmable temperature controller. Prior to heating, the system was purged with nitrogen gas at a flow rate of 100 mL min^{-1} for 15 min to establish an inert atmosphere. Pyrolysis was performed at selected temperatures with a heating rate of 10 °C min^{-1} and a residence time as specified from the CCD's output. The samples were heated at a rate of 10 °C min^{-1} to the desired final temperature (as specified in CCD's output) and maintained at that temperature for the specified residence time to complete carbonization. After pyrolysis, the system was allowed to cool to room temperature under continuous nitrogen flow to prevent oxidation of the produced char. The solid residue (biochar) was carefully removed and weighed to determine yield. Biochar yield (%) (Oladosu et al., 2024) was calculated as provided in Equation 6.

$$\text{Biochar Yield (\%)} = \frac{W_{\text{biochar}}}{W_{\text{dry}}} \times 100 \quad (6)$$

where $W_{biochar}$ is the mass of the recovered char. All experiments were conducted in triplicate to ensure reproducibility and the average values were reported.

Finally, the optimum yields of the biochar were subsequently analysed using scanning electron microscopy (SEM) (Hitachi SU 3500 model) and energy dispersive X-ray spectroscopy (EDX). SEM was used to determine the surface morphology and microstructure of the biochars whereas, EDX was used to determine to determine the elemental composition of the optimal biochar yield. These tests were conducted at Afe Babalola University, Ado Ekiti.

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Figure 2. The pyrolysis setup used for the experiment

3.0 Results and Discussion

3.1 Proximate and ultimate analyses

Table 2 summarizes the proximate and ultimate analyses of the investigated feedstocks. The proximate analysis performed on a dry basis reveals distinct compositional differences among CP, SM, and their 50/50 blend. CP contained 89.49 wt% volatile matter, 3.80 wt% fixed carbon, and 13.07 wt% Ash, whereas SM presented lower volatile matter (84.40 wt%) with comparable fixed carbon (9.72 wt%) and lower ash content (5.11wt%). The blended sample exhibited an elevated volatile fraction of 78.23 wt%, 4.86 wt% fixed carbon, and 6.85 wt% ash. Feedstocks rich in volatile matter are generally associated with enhanced production of condensable vapors and gaseous intermediates during thermochemical conversion, while elevated ash fractions may influence char formation and inorganic residue behavior (Ernest & Yakub, 2024). The measured higher heating values followed the trend: blend (24.60 MJ/kg) > CP (16.66 MJ/kg) > SM (15.92 MJ/kg), indicating improved energy density when cassava peel is incorporated. As shown in Table 2, the blend exhibits a higher carbon content (53.18 wt%) and lower oxygen content (36.41 wt%) than the individual feedstocks, resulting in a more favorable C/O ratio and improved energy density. In addition, the reduction in volatile matter (78.23 wt%) indicates enhanced carbonization during pyrolysis. These changes arise from synergistic interactions between the lignocellulosic structure of CP and the mineral-rich SM, which promote devolatilization and carbon enrichment (Kamesh et al., 2025).

Table 2. The proximate and ultimate analyses of the samples

Sample	Proximate Analysis				Ultimate analysis					HHV
	VM (wt%)	FC (wt%)	Ash (wt%)	MC (wt%)	C (wt%)	H (wt%)	N (wt%)	O (wt%)	S (wt%)	(MJ/kg)
SM	84.40	9.72	5.11	2.33	44.60	6.74	3.67	43.19	0.80	15.92
CP	89.49	3.80	13.07	2.70	43.15	8.43	4.57	43.76	0.09	16.66
CP-SM	78.23	4.86	6.85	10.06	53.18	6.54	3.29	36.41	0.58	24.60

The ultimate analysis further indicated carbon contents of 43.15, 44.60, and 53.18 wt% for CP, SM, and the blend, respectively. Hydrogen ranged from 6.54 – 8.43 wt%, nitrogen from 3.29 – 4.57 wt%, sulphur from 0.09–0.80 wt%, and oxygen from 36.41 – 43.76 wt%. These results fall within the range reported for agricultural residues in recent studies (Alnhoud et al., 2023; Ernest & Yakub, 2024; Siswantara et al., 2024; Waheed et al., 2023), which confirm the suitability of the selected materials for bioenergy applications.

3.2 Effect of pyrolysis conditions on biochar yield

The effect of pyrolysis temperature and residence time on the biochar yield obtained from CP, SM, and their blend (CP/SM 50/50) is illustrated in Figure 3, while the experimental results obtained using the CCD are presented in Table 3. The biochar yields varied significantly depending on the feedstock composition and pyrolysis conditions, indicating the strong influence of temperature and residence time on the thermal decomposition behaviour of the biomass materials. From Table 3, the biochar yield ranged between 50.0–93.0% for SM (0/100), 45.6–88.0% for CP (100/0), and 52.2–93.2% for the CP/SM (50/50) blend. The highest biochar yields were generally obtained at low pyrolysis temperatures (around 237–300 °C), while the lowest

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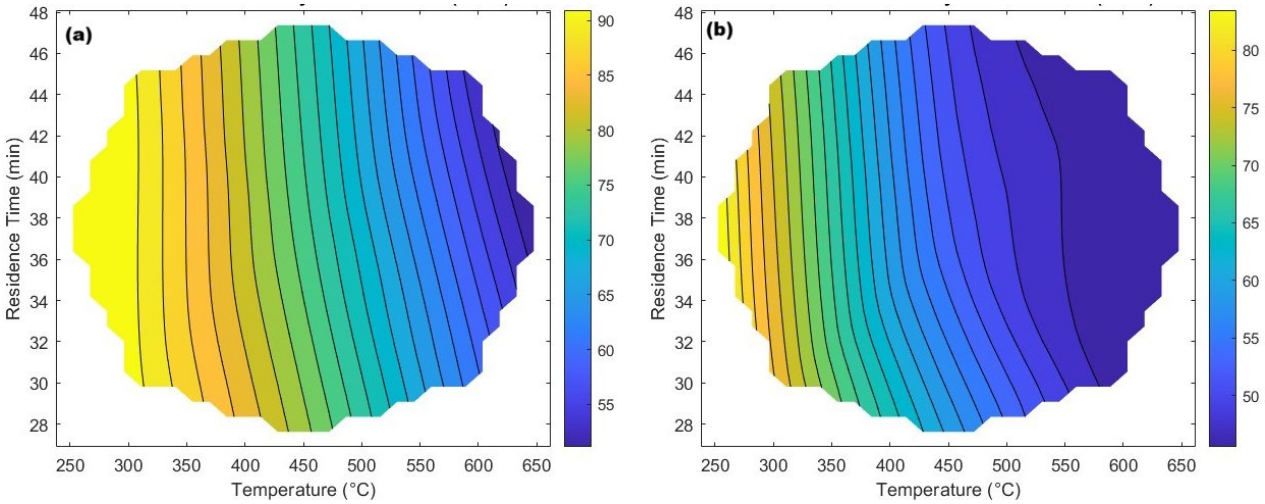
yields occurred at high temperatures above 600 °C. The co-pyrolysis of CP/SM (50/50) blend produced the highest biochar yield of 93.2% at 237.87 °C with residence time of 37.5 minutes.

Temperature was observed to be the most significant factor affecting biochar yield for all biomass compositions. As shown in the contour plots in Figure 3, biochar yield decreased consistently with increasing temperature for CP, SM, and their blend. At lower temperatures (approximately 237–300 °C), biomass decomposition is relatively limited, resulting in a higher retention of solid carbonaceous material. For instance, at 237.87 °C and 37.50 min, the maximum yields of 93.0%, 88.0%, and 93.2% were obtained for SM, CP, and CP/SM respectively (Table 3). This behaviour can be attributed to incomplete devolatilization at lower temperatures, where only moisture removal and partial decomposition of hemicellulose occur (Hamissou et al., 2023). Conversely, increasing the temperature to 600–662 °C significantly reduced the biochar yield. At 662.13 °C, the yield decreased to 50.0% for SM, 47.8% for CP, and 52.2% for the CP/SM blend. This reduction is primarily due to the extensive thermal degradation of cellulose and lignin, which promotes the release of volatile compounds and reduces the amount of residual solid char (Jalali et al., 2025). This trend is consistent with the typical pyrolysis behaviour of lignocellulosic biomass, where higher temperatures enhance secondary cracking reactions and volatile release, leading to lower char yields (Devi et al., 2020; Dhyani & Bhaskar, 2018).

Table 3. Experimental runs and responses based on CCD

S/N	Temperature (°C)	Residence Time (min)	CP/SM (0/100)	CP/SM (100/0)	CP/SM (50/50)
1	450.00	37.50	78.0	54.6	65.1
2	300.00	45.00	91.6	75.0	80.9
3	600.00	30.00	61.4	46.3	53.7
4	450.00	37.50	76.2	48.8	64.7
5	450.00	37.50	75.3	55.1	66.6
6	450.00	48.10	73.8	50.7	60.1
7	450.00	37.50	75.8	54.2	68.4
8	300.00	30.00	92.0	78.0	91.1
9	450.00	26.89	80.0	60.8	69.4
10	662.13	37.50	50.0	47.8	52.2
11	450.00	37.50	74.0	54.4	62.4
12	600.00	45.00	53.5	45.6	53.2
13	237.87	37.50	93.0	88.0	93.2

Residence time also influenced biochar production, although its effect was less pronounced than that of temperature. The contour plots indicate that increasing residence time generally resulted in a slight decrease in biochar yield, particularly at elevated temperatures. Longer residence times allow for prolonged exposure of the biomass to heat, facilitating further decomposition of the char matrix and promoting secondary reactions such as gasification and tar cracking (Fermanelli et al., 2020; Hoang et al., 2021). As a result, some of the solid carbon is converted into gaseous products, thereby reducing the char yield. However, at lower temperatures, the influence of residence time is relatively minimal since thermal decomposition reactions are slower.



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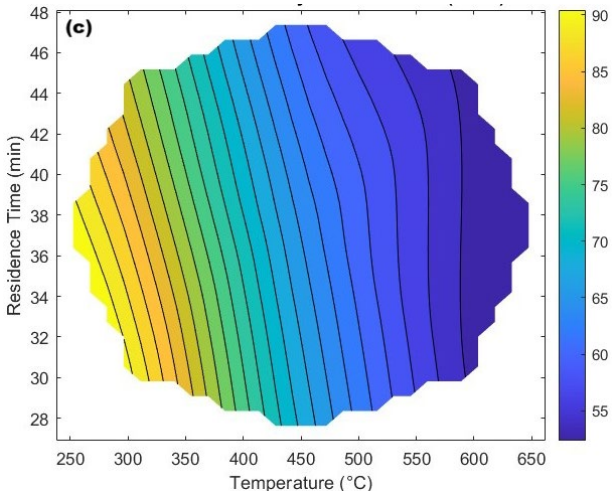

Figure 3. Contour plot for the biochar yields derived from the pyrolysis of (a) CP/SM (0/100), (b) CP/SM (100/0), and (c) CP/SM (50/50)

3.3 Effect of biomass composition

The feedstock composition significantly affected the biochar yield. Among the three feedstock configurations, SM generally produced higher char yields compared to CP. This behaviour can be attributed to the higher FC typically present in SM, which enhances char formation and stabilises the carbon structure during pyrolysis (Siswantara et al., 2024). Cassava peel, on the other hand, contains higher volatile matter content, which leads to greater volatilisation during pyrolysis and consequently lower char yields. This explains why the biochar yield for CP (100/0) was generally lower than that of SM (0/100) across most experimental conditions.

The co-pyrolysis of cassava peel and sheep manure (50/50) produced intermediate yields between the individual feedstocks. In some cases, the blend produced slightly higher yields than the individual materials, suggesting a possible synergistic interaction during co-pyrolysis. The minerals present in sheep manure may act as catalysts that promote char formation from the volatile compounds released from cassava peel. The results demonstrate that low to moderate pyrolysis temperatures (approximately 250–350 °C) are favourable for maximising biochar yield from cassava peel, sheep manure, and their blends. However, higher temperatures may still be desirable when the objective is to enhance other biochar properties such as surface area, porosity, and carbon stability, even though they reduce char yield. Furthermore, the co-pyrolysis of CP and SM offers a promising approach for biomass waste management, as it combines agricultural residues and animal manure to produce valuable carbon-rich biochar.

3.4 Statistical assessment of the model predictions in comparison to experimental data

Analysis of variance (ANOVA) was used to statistically investigate the response (biochar yields). Tables 4, 5, and 6 represent the ANOVA obtained for the biochar yields of CP/SM (0/100), CP/SM (100:0), and CP/SM (50/50) samples, respectively. The analyses of the P-value and F- value are crucial before approving any model; when the F-value is large, the model's dependability is better, whereas with a lower P-value, the model's significance is higher. Regression analysis was used to determine the correlation between the independent parameters (temperature and residence time) and the dependent variables (biochar yields). The derived model for predicting the biochar as a function of temperature and residence time, as obtained from the Design-Expert version 13.0 are provided in Equations 7, 8, and 9 for CP/SM (0/100), CP/SM (100/0), and CP/SM (50/50) samples, respectively.

Table 4. ANOVA for Quadratic model of CP/SM (0/100) Biochar

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	2182.73	5	436.55	183.65	< 0.0001	significant
A-Temp	137.54	1	137.54	57.86	0.0001	
B-Time	8.87	1	8.87	3.73	0.0947	
AB	14.06	1	14.06	5.92	0.0453	
A^2	29.91	1	29.91	12.58	0.0094	
B^2	2.72	1	2.72	1.15	0.3199	
Residual	16.64	7	2.38			
Lack of Fit	8.17	3	2.72	1.29	0.3935	not significant
Pure Error	8.47	4	2.12			

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For all feedstock compositions, the regression models were found to be highly significant, with model F-values of 183.66, 67.65, and 100.82 for CP/SM (0/100), CP/SM (100/0), and CP/SM (50/50), respectively, and corresponding p-values less than 0.0001. These results indicate that the developed quadratic models adequately represent the relationship between the process variables and biochar yield. The lack-of-fit tests for all models were statistically insignificant ($p > 0.05$), confirming that the proposed models provide a satisfactory description of the experimental data without significant systematic deviation. Consequently, the fitted models can be reliably used to predict the biochar yield within the investigated operating domain.

Table 5. ANOVA for Quadratic model of CP/SM (100/0) Biochar

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	2130.58	5	426.12	67.65	< 0.0001	Significant
A-Temp	224.55	1	224.55	35.65	0.0006	
B-Time	16.42	1	16.42	2.61	0.1505	
AB	1.32	1	1.32	0.2100	0.6607	
A²	349.72	1	349.72	55.52	0.0001	
B²	7.17	1	7.17	1.14	0.3214	
Residual	44.09	7	6.30			
Lack of Fit	16.97	3	5.66	0.8339	0.5411	not significant
Pure Error	27.13	4	6.78			

Among the process variables examined, pyrolysis temperature exhibited the most pronounced effect on biochar yield for all biomass ratios. The temperature term showed strong statistical significance with p-values of 0.0001, 0.0006, and <0.0001 for CP/SM (0/100), CP/SM (100/0), and CP/SM (50/50), respectively. This observation reflects the critical role of temperature in controlling biomass decomposition and volatilization during pyrolysis. Increasing temperature generally enhances the release of volatile compounds, thereby reducing the residual solid fraction (Jalali et al., 2025). In contrast, residence time did not significantly influence biochar yield within the investigated range, as indicated by p-values greater than 0.05 for all models. This suggests that most devolatilization reactions occur rapidly during pyrolysis and that extending the residence time beyond a certain threshold contributes marginally to further mass loss. The interaction between temperature and residence time was found to be statistically significant for the sheep manure (0/100) and blended biomass (50/50) systems, but not for cassava peel alone. This behavior indicates that synergistic interactions between process parameters become more pronounced when mixed feedstocks are subjected to co-pyrolysis.

$$Biochar_{CP/SM\ (100/0)} = 82.63 - 12.44A - 4.64B - 1.87AB - 2.07A^2 + 0.626B^2 \quad (7)$$

$$Biochar_{CP/SM\ (0/100)} = 61.98 - 15.89A - 6.31B + 0.575AB + 7.09A^2 + 1.02B^2 \quad (8)$$

$$Biochar_{CP/SM\ (50/50)} = 71.02 - 20.24A - 2.6B + 2.42AB + 3.88A^2 - 0.0955B^2 \quad (9)$$

Table 6. ANOVA for Quadratic model of CP/SM (50/50) Biochar

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	2095.59	5	419.12	100.82	< 0.0001	significant
A-Temp	363.98	1	363.98	87.55	< 0.0001	
B-Time	2.79	1	2.79	0.6705	0.4399	
AB	23.52	1	23.52	5.66	0.0490	
A²	104.74	1	104.74	25.20	0.0015	
B²	0.0634	1	0.0634	0.0152	0.9052	
Residual	29.10	7	4.16			
Lack of Fit	9.09	3	3.03	0.6055	0.6454	not significant
Pure Error	20.01	4	5.00			

The statistical adequacy of the developed quadratic models was further evaluated using several indicators, as summarized in Table 7. The coefficient of determination (R^2) values of 0.9924, 0.9797, and 0.9863 obtained for CP/SM (0:100), CP/SM (100:0), and CP/SM (50:50), respectively, demonstrate that the models successfully explain more than 97% of the variability in biochar yield. Similarly, the adjusted R^2 values remained in close agreement with the corresponding R^2, indicating the absence of redundant model terms and confirming the robustness of the regression models. The relatively low coefficients of variation (COV) (2.06–4.30%) and small standard deviation (SD) values (1.54–2.51) further indicate high precision and

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reliability of the experimental data. These findings confirm that the developed response surface models provide an accurate and reliable framework for predicting and optimizing biochar production from the investigated biomass systems (Mariyam et al., 2024; Tabish et al., 2024).

Table 7. Statistical analysis of the quadratic model for all the biochar samples

Biochar yield Models	R^2	Adjusted R^2	Mean	COV	SD
CP/SM (0/100)	0.9924	0.9870	74.97	2.06	1.54
CP/SM (100/0)	0.9797	0.9652	58.41	4.30	2.51
CP/SM (50/50)	0.9863	0.9765	67.77	3.01	2.04

3.5 Characterization of the modified biochar

The morphological and elemental analysis of CP/SM (50/50) biomass (as shown in Figure 4) revealed a heterogeneous texture characterized by compact, irregular granules with rough surfaces. The relatively large particle size (211.51 µm) and moderate bulk density (0.64 g/cm³) suggest a dense structure with limited porosity. The elemental composition shows a high carbon (46.32%) and oxygen (35.09%) content, indicating a partially carbonized material possibly with residual organic matter. The presence of nitrogen (14.53%) suggests the inclusion of protein-based components, while trace elements like calcium, phosphorus, and potassium point to some degree of mineral enrichment. This shows that CP/SM (50/50) biomass appears to be a moderately carbonized sample with dense physical characteristics and limited surface reactivity due to its low porosity.

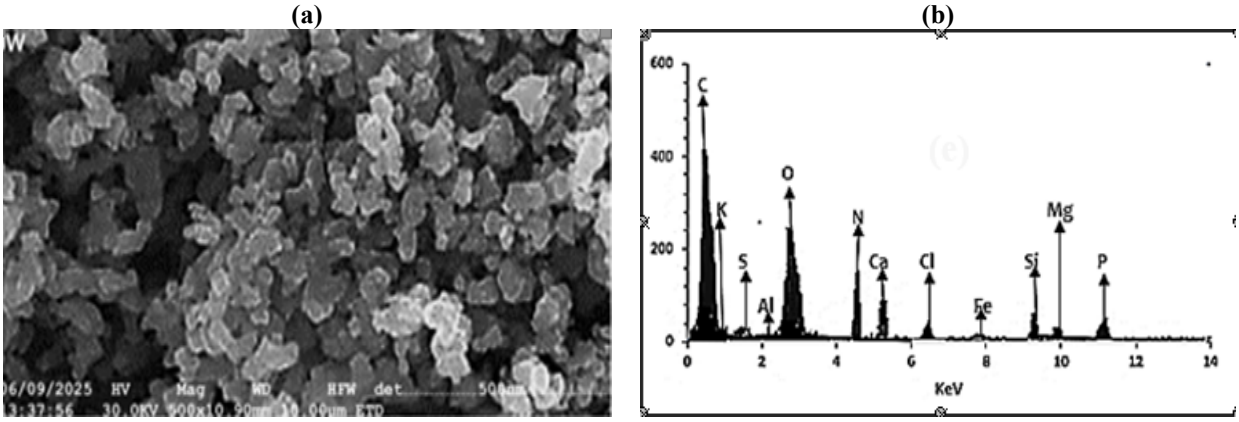

Figure 4. CP/SM (50/50) biomass characterization: (a) SEM image showing the surface morphology of the biomass, and (b) EDX spectrum indicating its elemental composition.

In contrast to CP/SM (50/50) biomass, the structure of CP/SM (50/50) biochar exhibits irregular mesopores with visible microcracks, indicating partial disintegration and an increase in surface roughness (as shown in Figure 5a). An improvement in porosity and surface area is indicated by the smaller particle size (68.13 µm) and lower bulk density (0.48 g/cm³). While the oxygen concentration (36.72%) is still rather high, indicating the presence of oxygenated functional groups, the carbon content (55.18%) is higher, suggesting more complete carbonization (as depicted in Figure 5b). The nitrogen content dropped by 2.45%, indicating further nitrogenous chemical breakdown during treatment. An increase in ash-related components that could affect adsorption or catalytic characteristics is indicated by the somewhat higher mineral content, especially calcium (2.67%) and phosphorus (0.83%).

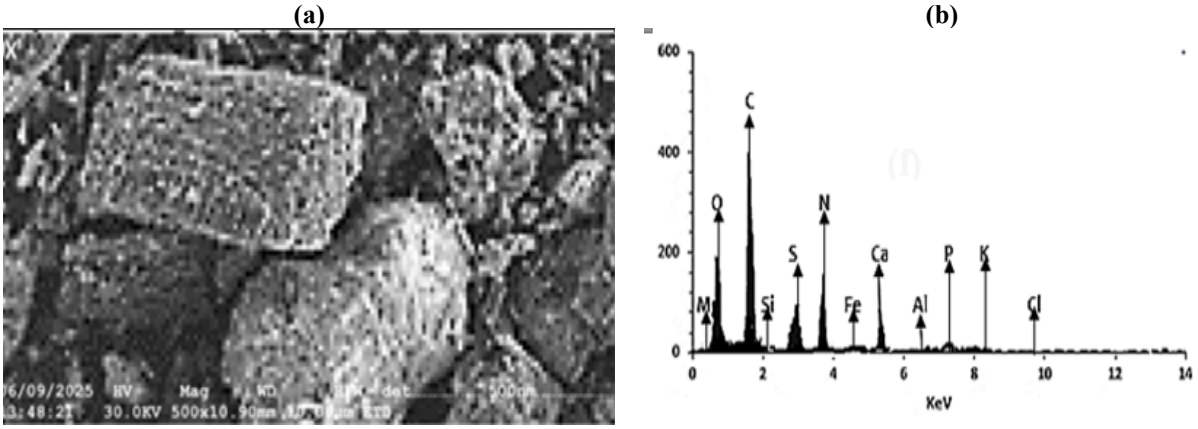

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Figure 5. CP/SM (50/50) biochar characterization: (a) SEM image showing the surface morphology of the biochar, and (b) EDX spectrum indicating its elemental composition.

The highly porous, honeycomb-like architecture of CP/SM (100/0) char, which has well-developed micropores, is a sign of advanced carbonization and structural evolution (as depicted in figure 6a). A lightweight, porous substance is indicated by a further drop in particle size to 36.21 µm and a bulk density of 0.32 g/cm³. The carbon concentration dramatically rises to 65.09% while the oxygen level falls to 27.17%, indicating effective carbonization and volatile component reduction a shown in Figure 6b. The sample's catalytic or adsorption performance may be influenced by the modest quantities of calcium, phosphorus, and potassium, which indicate improved mineral retention. Because of its high porosity and carbon purity, the structure and content of CP/SM (100/0) make it appropriate for uses such energy storage, filtration, and the manufacturing of activated carbon.

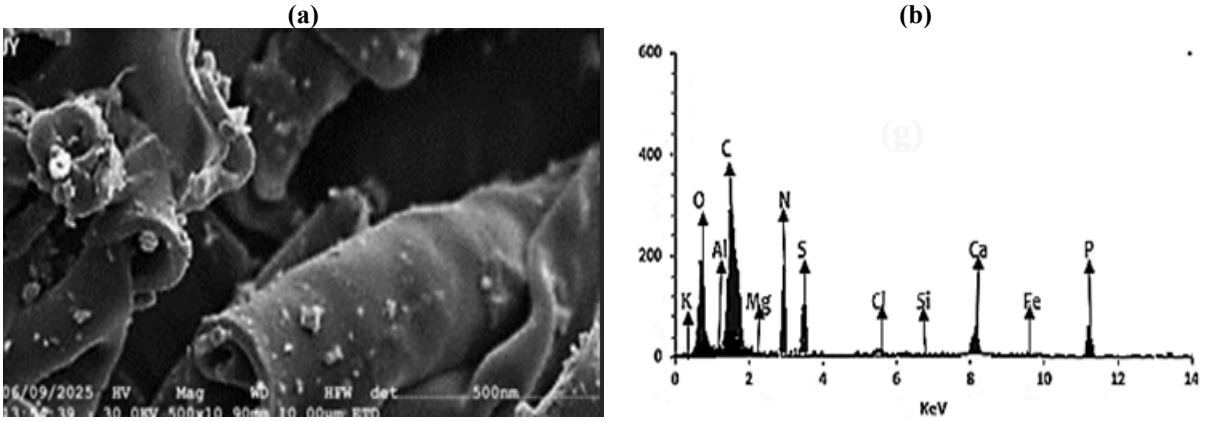

Figure 6. CP/SM (100/0) biochar characterization: (a) SEM image showing the surface morphology of the biochar, and (b) EDX spectrum indicating its elemental composition.

Lastly, the most advanced structural alteration is shown in CP/SM (0/100) char, which exhibits brittle, fractured sheets with many voids and micropores (Figure 7a). The lowest bulk density (0.17 g/cm³) and smallest particle size (16.87 µm) indicate a lightweight, extremely porous substance that is characteristic of well-activated carbon structures. Near-complete carbonization and high heat treatment are indicated by the carbon content peaking at 74.47% and the oxygen content falling precipitously to 16.05% (Figure 7b). Significant inorganic residue that could improve ion-exchange capacity is suggested by the increased presence of mineral elements like calcium (3.58%), phosphorus (1.74%), and potassium (1.19%). For adsorption, catalysis, or energy storage applications, CP/SM (0/100) may be the most efficient sample due to its excellent porosity, low density, and high carbon purity.

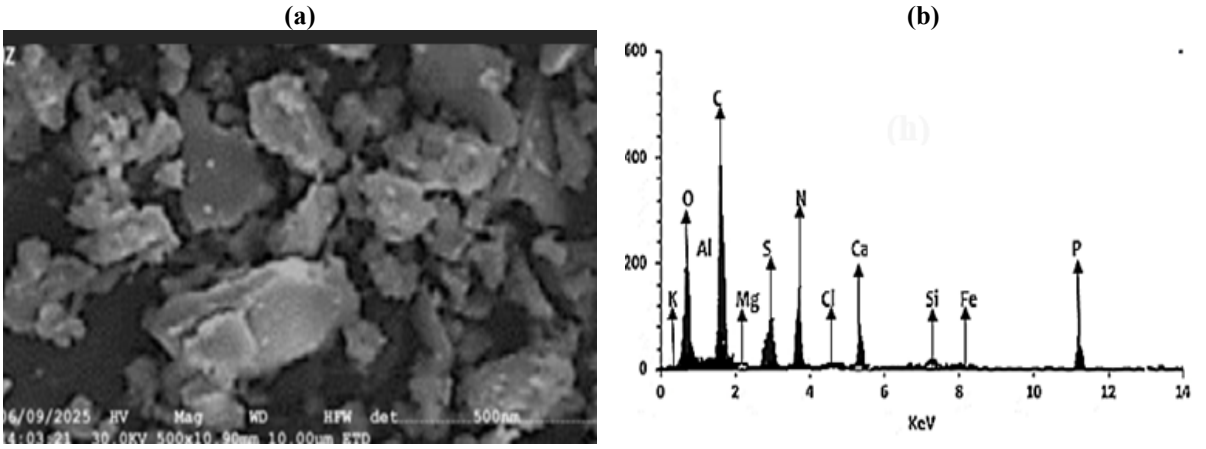

Figure 7. CP/SM (0/100) biochar characterization: (a) SEM image showing the surface morphology of the biochar, and (b) EDX spectrum indicating its elemental composition.

4.0 CONCLUSION

This study investigated the co-pyrolysis of cassava peel and sheep manure using a fixed-bed reactor and modeled the process with response surface methodology. Biochar yield was strongly influenced by feedstock composition, pyrolysis temperature, and residence time, with temperature being the most significant factor.

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Higher yields were achieved at lower temperatures (237–300 °C), while yields decreased at temperatures above 600 °C. The 50/50 blend of cassava peel and sheep manure produced the highest yield (93.2%) at 237.87 °C and 37.5 minutes. Statistical models showed high accuracy ($R^2 > 0.97$). Sheep manure yielded more biochar than cassava peel, but their combination provided stable and improved performance. Co-pyrolysis of these materials is an effective and sustainable approach for biochar production and offers valuable predictive tools for process optimization and scale-up.

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