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Physicochemical Characterization of Plant- and Manure-Derived Biochars Produced under Identical Pyrolysis Conditions: A Comparative Study of Malaysian Agricultural Wastes

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ABSTRACT

The accumulation of agricultural wastes such as crop residues and animal manures in Malaysia are increasingly generated and are often inadequately managed, causing environmental hazards. However, these wastes have significant economic value and potential to be transformed into useful products like biochar within a circular economy framework. This study evaluated physicochemical properties of six selected agricultural wastes between crop-based residue i.e. rice husk, coconut husk, oil palm empty fruit bunch, and animal-based manure i.e. cow manure, goat manure, and chicken manure by producing biochar at 500 °C for 30 minutes under laboratory conditions. Biochar yields ranged from 32% to 50%. Manure-derived biochars generally exhibited higher yields. Ash content differed from 9% to 55% and was higher in manure-derived biochar due to greater mineral composition. Crop residue biochar showed higher moisture content, higher total carbon, more developed pore structures in SEM, and lower H:C molar ratios (<0.7) which demonstrating greater stability. All biochar except rice husk biochar featured alkaline properties (pH 7.51–9.46). Animal manure biochar is nutrient-rich in macro- and micronutrients, with chicken manure biochar showing the highest nutrient levels (e.g., P - 2.44%, K – 5.43%, Ca – 9.20%) but also a very high electrical conductivity (23.12 dS/m) and poor pore structure. This comparative study provides fresh insights for optimizing feedstock selection in scalable and cost-effective biochar production.

***Key words**: Biochar, lab-scale pyrolysis, animal manure, physico-chemical analysis*

INTRODUCTION

Waste management has become a global threat causing serious problem as human activities continue to generate huge number of wastes in the form of solid, liquid, gaseous, and even hazardous radioactive waste (Demirbas, 2011). The most common disposal method for these wastes is landfilling due to its low cost, despite the long-term risks to both humans and the environment. The agricultural sector is a major contributor to the national economy of Malaysia, but the abundance of crop residues has created significant disposal concerns (Tang *et al*., 2025). Malaysia reportedly dumps over one million tonnes of agricultural wastes into landfills every year greater than many other nations worldwide (Farhana Fadzil & Amira Othman, 2021). Thus, urgent need for sustainable alternatives to conventional waste management practices are needed to overcome these challenges (Parthasarathy *et al*., 2022).

As a potential solution for sustainable agriculture, environmental management, and climate change mitigation, a carbon-rich material called biochar is grabbing attention worldwide (Waheed *et al*., 2025). International Biochar Initiative (IBI) states that biochar offers integrated benefits, including improved soil fertility, enhanced carbon sequestration,

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reduced land-use pressures, and support for food security and economic development. Biochar can be produced through various thermochemical processes, such as pyrolysis and gasification, with pyrolysis being a promising environmentally friendly conversion of agricultural residues into stable carbon-rich products (Adekanye *et al*., 2025). Majority of the lab-scale pyrolysis conducted under oxygen-limited conditions at 400–800 °C, producing biochar together with volatile gases and condensable organic vapours (Rambhatla *et al*., 2025).

Carbonizing plant- and animal-derived residues not only provides a sustainable alternative to traditional charcoal but also represents a valuable route for resource recovery (Shinogi & Kanri, 2003). Previous studies have demonstrated that plant-based biochar enhances soil organic carbon storage, whereas manure-derived biochar increases nutrient availability and crop yields (Sapkota *et al*., 2025). However, many studies evaluate these biochars under varying pyrolysis conditions, making direct comparisons difficult. Moreover, experimental data directly comparing the physicochemical properties of plant- and animal-derived biochars produced from Malaysian agricultural wastes under identical, controlled laboratory conditions remain limited. Thus, this knowledge gap hinders the ability of farmers, waste managers, and industry to make informed decisions about which feedstock to use for a specific purpose, such as soil fertilization versus long-term carbon sequestration.

Such comparative evaluation is essential for optimising biochar production strategies and selecting appropriate feedstocks based on intended applications within sustainable waste management and circular economy frameworks. Therefore, this study conducts a comparative physicochemical evaluation of plant- and animal-derived biochars produced from selected Malaysian agricultural wastes under controlled laboratory pyrolysis conditions. The specific objectives were to: (i) quantify biochar yield, moisture and ash percentage (ii) analyze elemental and nutrient composition, (iii) determine pH and electrical conductivity, and (iv) examine surface morphology, in order to assess their suitability for soil amendment and waste valorization.

MATERIALS AND METHODS

Figure 1 stated the methodology of the study, with the chronological flow of how this study has been conducted.

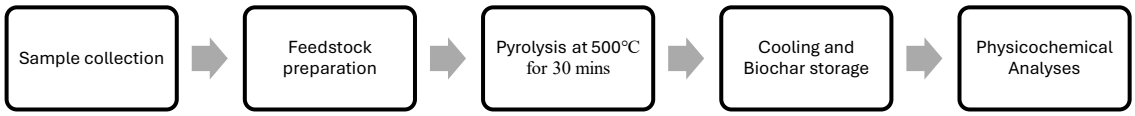


Figure 1. The flow diagram of the overall methodology

Sample collection & feedstock preparation

Six agricultural residues were selected: three plant-based materials (rice husk, coconut husk, oil palm empty fruit bunch) and three animal-based manures (cow, goat, chicken manure). All feedstocks were oven-dried at 60°C to constant weight. Coconut husk and empty fruit bunch (EFB) were cut into smaller pieces prior to drying to ensure uniform heat exposure. Dried samples were stored in a desiccator until pyrolysis.

Pyrolysis conditions

Biochar was produced through slow pyrolysis at 500 °C for 30 min using a Thermolyne 62700 laboratory furnace under oxygen-limited conditions. Approximately 15 ± 1 g of each dried feedstock were placed in covered porcelain dishes before pyrolysis. After heating, samples

were allowed to cool to room temperature inside the furnace. All biochars were then ground and stored in airtight bags for subsequence analysis (**Figure 2**).



Figure 2. Different types of biochar after pyrolysis at 500°C for 30 minutes using a laboratory furnace

Physicochemical analyses

Yield, moisture and ash

Biochar yield (Eq.1) was calculated as:

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$$Biochar\ Yield\ (\%) = (\frac{dry\ mass\ of\ biochar\ (g)}{dry\ mass\ of\ biomass\ (g)}) \times 100$$ ----- Eq. 1

The moisture content and total ash of the respective biochar samples were determined according to the IBI Biochar Standard v2.1 (2015).

pH and Electrical Conductivity (EC)

Biochar pH and EC were measured following IBI Biochar Standard v2.1 (2015) using a 1:5 (v/v) biochar: deionised water suspension. Mixtures were shaken for 90 min, equilibrated for 24 h, and analysed using benchtop pH and EC meters.

Macronutrients and micronutrients

Macronutrients (P, K, Ca, Mg) and micronutrients (Zn, Fe, Cu) were quantified using the dry-ashing method (550 °C, 16 h). Ash residues were digested with HCl and HNO_3, diluted, and analysed using an Auto Analyzer (for P) and Atomic Absorption Spectrophotometry (AAS).

CHNS elemental composition

Carbon, hydrogen, nitrogen, and sulfur contents were determined using a CHNS analyser 628 Series at the Material Characterisation Laboratory, UPM.

Scanning Electron Microscopy (SEM)

Surface morphology was examined using a scanning electron microscope (SEM) at the Institute of Bioscience, UPM.

Statistical analysis

Data were analyzed using one-way ANOVA followed by LSD tests at $p < 0.05$ in R version 4.4.2. All experiments were conducted in triplicate.

RESULTS AND DISCUSSION

Table 1 shows the biochar yield, moisture content, total ash percentage, pH and EC for all six types of biochar used in this experiment. From **Table 1**, the chicken manure biochar (CMB) exhibited the highest total ash content at 54.66%, followed by cow dung biochar (CDB) at 40.08%. In contrast, goat dung biochar (GDB) and rice husk biochar (RHB) showed comparable ash levels of 32.63% and 32.07%, respectively. The lowest ash contents were observed in oil palm empty fruit bunch biochar (EFBB) and coconut husk biochar (CHB), at 12.91% and 9.49%, with no significant difference between them. This pattern aligns with previous reports indicating that animal-waste-derived biochars generally contain higher mineral ash levels than plant-based biochars (Li *et al*., 2018) due to the higher inorganic mineral content of manure feedstocks. These results further support the distinct mineral composition of animal- and plant-derived feedstocks.

Significant differences in biochar yield were observed across various biomass types at a constant pyrolysis temperature of 500°C. From **Table 1**, chicken manure biochar (CMB) had the highest yield at 50.07%. The lowest yield was observed in oil palm empty fruit bunch biochar, at about 31.51%. Comparatively, biochar produced from animal waste biomass had a higher yield percentage than biochar made from plant waste biomass. The yield percentage of rice husk biochar (RHB) and goat dung biochar (GDB) was not significantly different. Therefore, biochar yield was dependent on both feedstock characteristics and pyrolysis conditions; under a fixed pyrolysis temperature, yield was primarily governed by the inherent properties of the feedstock (Xiao *et al*., 2022). Coconut husk biochar (CHB) exhibited the

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highest moisture content (5.93%). Lastly, the chicken manure biochar (CMB) had the lowest moisture content, about 1.47%, compared to the other biochars.

Table 1 : Total ash, yield, and moisture content percentages for different types of biochar

Types of biochar	RHB	CHB	EFBB	CDB	GDB	CMB
Total Ash (%)	32.07 ± 0.67 **c**	9.49 ± 1.69 **d**	12.91 ± 0.35 **d**	40.08 ± 3.62 **b**	32.63 ± 0.31 **c**	54.66 ± 2.42 **a**
Yield %	43.09 ± 0.12 **c**	37.60 ± 0.30 **d**	31.51 ± 0.09 **e**	46.33 ± 0.09 **b**	42.58 ± 0.06 **c**	50.07 ± 0.22 **a**
Moisture content (%)	3.33 ± 0.42 **b**	5.93 ± 0.31 **a**	3.93 ± 0.42 **b**	2.53 ± 0.23 **c**	2.53 ± 0.31 **c**	1.47 ± 0.64 **d**
pH	6.67 ± 0.02 **f**	7.51 ± 0.12 **e**	9.25 ± 0.07 **b**	8.84 ± 0.00* **d**	8.98 ± 0.05 **c**	9.46 ± 0.08 **a**
EC (dS/m)	1.52 ± 0.02 **d**	1.28 ± 0.29 **d**	4.3 ± 0.13 **b**	4.51 ± 0.16 **b**	3.39 ± 0.23 **c**	23.12 ± 0.36 **a**

Notes: Means ± SD (n=3); 0.00* indicates a standard deviation of less than 0.005, followed by the different letters were significantly different using the LSD ($p < 0.05$; RHB-Rice Husk Biochar, CHB-Coconut Husk Biochar, EFBB-Oil Palm Empty Fruit Bunch Biochar, CDB-Cow dung Biochar, GDB- Goat dung Biochar, CMB-Chicken Manure Biochar.

Pearson's Correlations

A comparison between ash percentage with yield was performed using Pearson Correlation, as shown in **Figure 3**. Pearson correlation coefficient was computed to assess the relationship between total ash percentage and yield percentage of different types of biochar. The two variables showed a strong, positive correlation ($r = 0.912$), and the relationship was significant ($p < 0.001$ at alpha = 0.05). This indicates a strong correlation between the total ash percentage and the yield percentage of biochar. This strong positive correlation ($r = 0.912$) is expected, as yield at this temperature is largely determined by the biomass's inorganic, non-combustible fraction (ash), which remains as a solid residue.

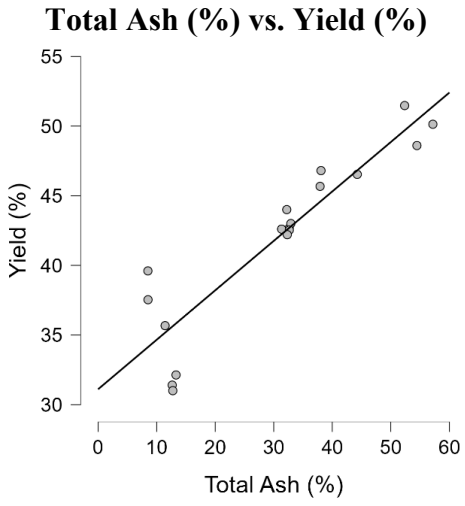


Figure 3. Scatter plot of the relationship between yield (%) and total ash (%) of different types of biochar. Source: JASP Team (2025). JASP (Version 0.19.3) [Computer software].

All the biochars, except rice husk biochar (RHB), exhibit alkaline properties, with pH values of 7.51–9.46 (**Table 1**). According to Murtaza *et al*. (2022), biochar typically has a pH range of 7.2–10.3 and is alkaline. Another study also suggests that the optimal temperature for biochar production is 500℃, at which all produced biochars exhibit alkaline pH (Yuan *et al*., 2011). However, in this study, only rice husk biochar (RHB) shows a slightly acidic pH of about 6.67. Similar situation was observed by Ammal *et al*. (2020) where biochar produced at

500°C shows a pH of 6.5 where they claim biochar produced from rice husk grown in slightly acidic soil will also exhibit slightly acidic properties. This shows that crop residues harvested from different growing conditions also influence the pH of biochar so checking the pH of raw biomass before biochar conversation process will give good direction on the pyrolysis temperature need to be used. Conversely, rice husk biochar produced at 550°C for 30 mins has a pH of 9.29 (Fu *et al*., 2022). The pH varies with pyrolysis temperature and feedstock type, with pH values across different biochars ranging from 5.52 to 10.10 as the pyrolysis temperature increased from 300 °C to 600 °C (Almutairi *et al*., 2023).

The EC level was the highest in chicken manure biochar (CMB), at about 23.12 dS/m (**Table 1**). The oil palm empty fruit bunch biochar (EFBB) and cow dung biochar (CDB) were not significantly different in EC level, with values of 4.30 dS/m and 4.51 dS/m, respectively. The lowest EC level was observed in rice husk biochar (RHB) and coconut husk biochar (CHB), which recorded 1.52 dS/m and 1.28 dS/m, respectively, and were not significantly different. From our observation, the exceptionally high EC in CMB reflects the concentration of soluble inorganic salts during pyrolysis, which may restrict its direct application due to potential salinity stress. A value this high means CMB would need to be used very cautiously as a soil amendment, as it could cause salt stress in plants. It might be more suitable for other applications, like a component in growing media for salt-tolerant plants or in contaminated land remediation where high salinity is less of a concern.

Macro and micronutrient

From **Table 2**, The chicken manure biochar (CMB) exhibited the highest macronutrient content among all the biochars, followed by goat dung biochar (GDB), except for its potassium concentration. Nitrogen contents differed significantly across the six biochars, with coconut husk biochar (CHB) showing the lowest value at approximately 0.4%. All three plant-derived biochars contained less than 1% nitrogen, in contrast to the animal-waste-derived biochars, which exhibited considerably higher nitrogen levels. No significant differences were observed among the three-plant waste biochars in terms of phosphorus content, whereas significant variation occurred among the three-animal waste biochars.

Potassium content also varied significantly among the biochars, except between cow dung biochar (CDB) and goat dung biochar (GDB), which did not differ. Rice husk biochar (RHB) recorded the lowest potassium content at 0.6%. Notably, CMB was exceptionally rich in calcium, containing 9.2%, far exceeding all other biochars. GDB and oil palm empty fruit bunch biochar (EFBB) had the next-highest calcium concentrations, with no significant difference between them. Conversely, RHB, CDB, and CHB showed no significant difference in calcium content, all containing less than 0.7%.

Magnesium concentrations also differed significantly among the six biochars, with CMB again showing the highest value at approximately 1.75%, while RHB recorded the lowest at around 0.45%. Similarly, sulphur content was highest in CMB, followed by CDB and GDB, which did not differ significantly. All plant-waste biochars contained less than 0.1% sulphur; however, EFBB differed significantly from both RHB and CHB. In terms of micronutrient chicken manure, biochar has the highest value among all other biochars. The animal waste biochar contains a higher iron percentage than other plant waste biochar (**Table 2**). For zinc and copper percentages, no significant differences were observed among the biochars, except for chicken manure biochar.

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Overall, the results indicate that biochars derived from animal wastes contain higher macronutrient levels than those produced from plant-based biomass. This is consistent with previous findings showing that animal waste is an excellent feedstock for generating nutrient-rich biochar capable of enhancing plant performance (Parthasarathy *et al*., 2022). This pattern is further supported by evidence that feedstock type strongly influences biochar nutrient profiles, with manure-based biochars generally richer in P, Ca, and Mg, while crop residue–and wood-derived biochars contain the lowest levels of these nutrients (Ippolito *et al*., 2020). Thus, the elevated nutrient concentrations in manure-derived biochars likely result from the thermal concentration of mineral constituents inherently present in animal wastes.

Table 2: Nutrient contents

Types of Biochar	RHB	CHB	EFBB	CDB	GDB	CMB
N %	0.63 ± 0.03 e	0.41 ± 0.00* f	0.92 ± 0.00* d	1.65 ± 0.01 c	1.92 ± 0.01 b	2.38 ± 0.01 a
P %	0.23 ± 0.03 d	0.27 ± 0.06 d	0.22 ± 0.00* d	0.41 ± 0.01 c	0.66 ± 0.01 b	2.44 ± 0.03 a
K %	0.60 ± 0.03 e	2.08 ± 0.15 c	3.25 ± 0.04 b	1.52 ± 0.02 d	1.40 ± 0.20 d	5.43 ± 0.12 a
Ca %	0.69 ± 0.13 c	0.52 ± 0.22 c	1.18 ± 0.00* b	0.67 ± 0.19 c	1.21 ± 0.31 b	9.20 ± 0.41 a
Mg %	0.45 ± 0.00* f	0.54 ± 0.02 e	0.65 ± 0.04 d	0.77 ± 0.03 c	0.91 ± 0.03 b	1.75 ± 0.04 a
S %	0.04 ± 0.00* d	0.03 ± 0.00* d	0.09 ± 0.00* c	0.30 ± 0.01 b	0.29 ± 0.00* b	0.47 ± 0.02 a
Fe %	0.48 ± 0.22 c	0.39 ± 0.08 c	0.39 ± 0.11 c	4.20 ± 0.00* ab	3.81 ± 0.36 b	4.43 ± 0.61 a
Zn %	0.17 ± 0.11 b	nd	nd	0.10 ± 0.05 b	0.15 ± 0.00* b	2.35 ± 0.09 a
Cu %	nd	0.02 ± 0.01 b	0.01 ± 0.00* b	0.02 ± 0.01 b	0.02 ± 0.01 b	0.28 ± 0.01 a

Note: Means ± SD (n=3); 0.00* indicates a standard deviation of less than 0.005, followed by the different letters were significantly different using the LSD ($p < 0.05$; nd=not detectable. RHB-Rice Husk Biochar; CHB-Coconut Husk Biochar; EFBB-Oil Palm Empty Fruit Bunch Biochar; CDB-Cow dung Biochar; GDB- Goat dung Biochar; CMB-Chicken Manure Biochar**.**

Essential elements

All six biochars showed significant differences in their carbon and hydrogen contents (**Table 3**). Coconut husk biochar (CHB) had the highest carbon content (64.28%), while chicken manure biochar (CMB) had the lowest. In contrast, empty fruit bunch biochar (EFBB) recorded the highest hydrogen content, and CMB again had the lowest. According to the International Biochar Initiative (IBI) Standard v2.1 (2015), carbon and hydrogen are key indicators of carbon stability, typically assessed using the molar hydrogen-to-organic carbon (H/Corg) ratio. Similarly, the European Biochar Certificate (EBC) recommends both H/Corg and O/Corg ratios to classify biochar stability, with upper limits of 0.7 and 0.4, respectively, to ensure the presence of stable aromatic carbon structures and to distinguish biochar from incompletely carbonised materials.

Table 2: shows the essential element percentage and the hydrogen to total carbon ratio

Types of Biochar	RHB	CHB	EFBB	CDB	GDB	CMB
C %	46.80 ± 0.19 c	64.28 ± 0.03 a	63.84 ± 0.45 b	41.76 ± 0.19 e	45.37 ± 0.24 d	33.23 ± 0.05 f
H %	2.87 ± 0.01 e	3.43 ± 0.02 b	3.75 ± 0.04 a	3.09 ± 0.02 d	3.36 ± 0.01 c	2.53 ± 0.01 f
H: C_{tot} (molar ratio)	0.7	0.6	0.7	0.9	0.9	0.9

Note: Means ± SD (n=3) followed by the different letters were significantly different using the LSD ($p < 0.05$). Note: RHB-Rice Husk Biochar, CHB-Coconut Husk Biochar, EFBB-Oil Palm Empty Fruit Bunch Biochar, CDB-Cow dung Biochar, GDB- Goat dung Biochar, CMB-Chicken Manure Biochar.

However, total organic carbon could not be measured due to limited access to a TOC analyser. Therefore, the hydrogen-to-total-carbon molar ratio was used as a practical alternative indicator of carbon stability. Although exact H/Corg values could not be determined, the H/Total C ratios suggest that plant-residue biochars possess relatively stable, aromatic carbon, whereas manure-derived biochars exhibit lower carbon stability. These interpretations should be considered approximate due to the absence of organic carbon measurements. Plant-based

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biochars tend to contain higher carbon content but lower concentrations of essential plant nutrients compared to manure-based biochars, as plants assimilate only a small proportion of soil elements (Ippolito *et al*., 2015).

SEM analysis

According to the Scanning Electron Microscope (SEM) analysis, a more visible pore structure was observed among all the plant waste biochars (Refer **to Figure 4**). The visible pore structure was seen among cow dung biochar and goat dung biochar. However, a lack of visible pore structure was observed in chicken manure biochar for both 2500 and 5000 magnifications. It is interesting that cowdung biochar and goat dung biochar show some porosity, while chicken manure biochar does not. This could be due to the finer, more compacted nature of the manure itself before pyrolysis.

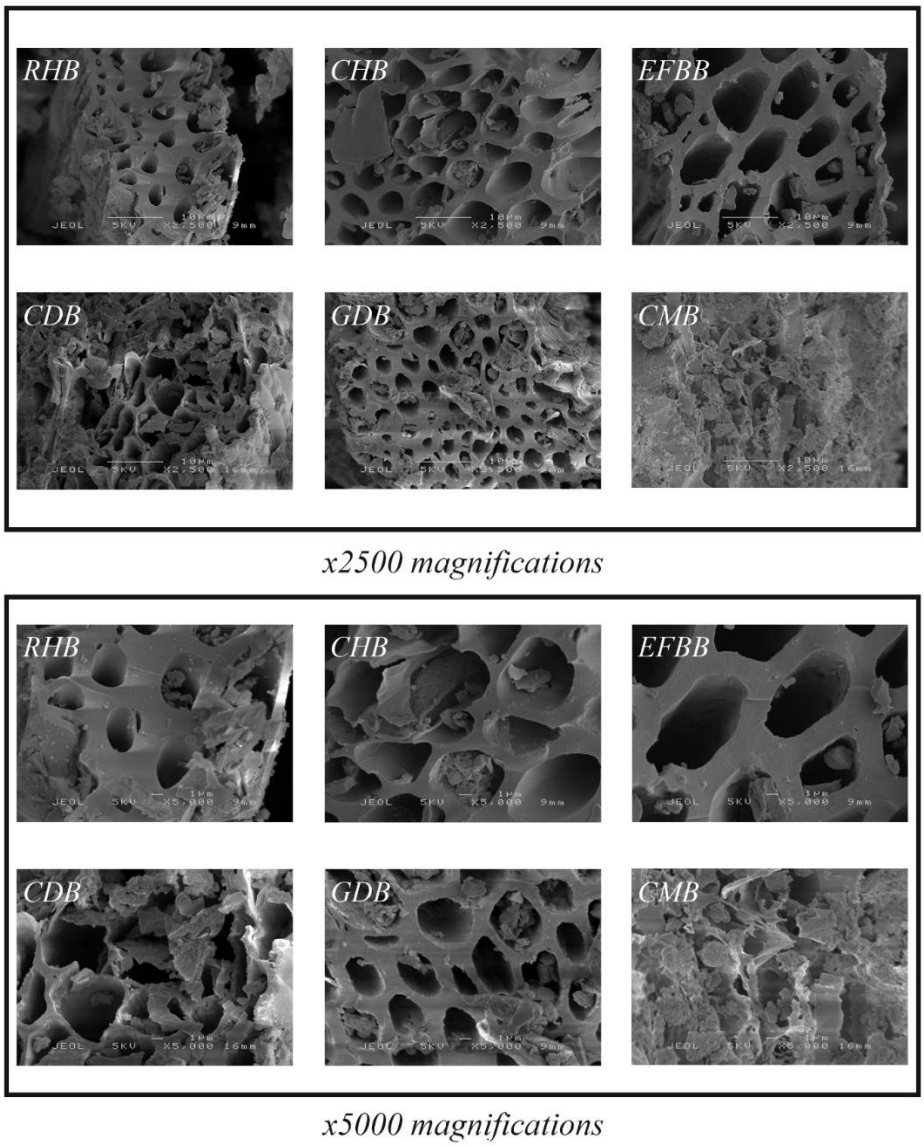


Figure 4: Images of Scanning Electron Microscope (SEM) Analysis of ×2500 and ×5000 magnifications for all the biochar.
Note: RHB-Rice Husk Biochar; CHB-Coconut Husk Biochar; EFBB-Oil Palm Empty Fruit Bunch Biochar; CDB-Cow dung Biochar; GDB- Goat dung Biochar; CMB-Chicken Manure Biochar.

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CONCLUSION

Both plant and animal wastes have a significant impact on biochar studies, as evidenced by their effects on physical and chemical properties. Animal-derived biochars, particularly from chicken manure, demonstrated superior nutrient enrichment but estimated lower carbon stability (as indicated by higher H/C ratios) and limited pore development. Future optimization of pyrolysis temperature-time profiles and co-pyrolysis of mixed feedstocks could enhance biochar stability and field applicability. Future research should explore co-pyrolyzing a high-nutrient but low-stability feedstock like chicken manure with a high-carbon, structural feedstock like coconut husk. This could potentially produce a biochar with both agronomic value and carbon sequestration potential. Furthermore, optimizing pyrolysis temperature below 500°C might improve the yield and nutrient retention of manure biochars, while higher temperatures could enhance the stability of crop residue biochars. Thus, further studies are needed with precise specifications of pyrolysis temperature and time to fully realise the potential of many other agricultural wastes for biochar utilisation.

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