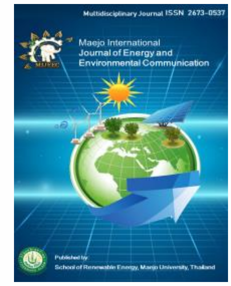
Maejo International Journal of Energy and Environmental Communication

Journal homepage: https://ph02.tci-thaijo.org/index.php/MIJEEC



ARTICLE

Comparative analysis of biochar production from agricultural residues: yield optimization and physicochemical characterization using modified barrel pyrolysis in Northern Thailand

Nirmala Bhuvana Chandra Ramisetty[1], Garan Sujinda[2], Thanathip Janthima[2], Siriset Saipanyoyai[2], Prakash Bhuyar[1, *]

[1] International Industry and Agriculture Innovation Research Center (IIAR), International College, Maejo University, Chiang Mai, 50290, Thailand

[2]The Prince Royal's College, Wat Ket, Mueang Chiang Mai District, Chiang Mai 50000, Thailand

A R T I C L E I N F O

Article history:
Received 4 June 2025
Received in revised form
30 June 2025
Accepted 2 July 2025

Keywords:
Biochar
Pyrolysis
Agricultural waste valorization
FTIR spectroscopy
Sustainable agriculture

A B S T R A C T

Improper management of agricultural waste leads to greenhouse gas emissions and soil degradation and therefore, this study aims to investigate biochar production from rice husk, rice straw, corn husk and longan wood using a modified barrel pyrolysis system in Chiang Rai, Thailand. Around 4.5-15 kg of each residue underwent pyrolysis at oxygen-limited conditions for 2.5-3 hours, with biochar yields being determined by weight and physicochemical properties being analyzed by Fourier Transform Infrared (FTIR) spectroscopy. Longan wood exhibited the highest biochar yield (43.3%), followed by rice straw (40.0%), corn husk (36.0%) and rice husk (31.1%) with FTIR revealing the presence of distinct functional group, such as peaks of silica of rice husk biochar (~1050 cm^{-1}), enhanced aromatic structure (1600-1650 cm^{-1}) of Longan wood biochar and O-H (~3400 cm^{-1}) and C=C stretching in all samples, which are typical of carbonaceous materials. The effectiveness of the modified barrel pyrolysis system in the conversion of agricultural waste into biochar with feedstock-specific properties for soil amendment and carbon sequestration.

1. Introduction

Agricultural residues are increasing at an alarming rate and posing a serious problem to present farming systems (Kaewdiew et al., 2019; Smith et al., 2020). Every year, agricultural activities produce about 140 billion metric tons of biomass waste, and Asia accounts for almost 50% of the amount (Kumar et al., 2021; Nguyen et al., 2022). Thailand is an example of such a problem, where rice cultivation produces 30 to 40 million tons of straw and husk annually. As much of this gets burnt in the fields, this has become a major source of air pollution and carbon emission (Dussadee et al., 2014; Pongpat et al., 2017; Ramaraj & Dussadee, 2015). Depending on open burning or uncontrolled decomposition, there are significant releases of CO_2, CH_4, and N_2O (Chen et al., 2019; Dang et al., 2023). This is not merely a climate issue. It is a lost opportunity to take the raw waste and convert it into a valuable product (Laird et al., 2009). Biochar is essentially a carbon-dense solid produced by the heating of biomass with very little oxygen (Lehmann & Joseph, 2015). This is referred to as pyrolysis, and typically occurs between 300 °C and 700 °C. During this stage, the organic material is broken down into three components, viz., solid biochar (10-50% of weight), liquid bio-oil (20-50%), and syngas (15-40%) (Tripathi et al., 2016). Importance to agriculture is its physical properties of biochar (Gotore et al., 2024). Due to its very porous characteristics and the negative surface charge it assumes, it has a sponge-like effect on the soil. It holds on to water, prevents nutrients from being washed away, and can even trap carbon

* Corresponding author.
E-mail address: prakash@mju.ac.th (Bhuyar P.)

underground for centuries (Woolf et al., 2010). Studies show that the use of biochar can increase crop yields by 10% to 40% in the tropical regions where the soil is naturally acidic or nutrient-deficient (Jeffery et al., 2017). The principle of the pyrolysis process is based on thermal decomposition in the absence of, or with limited, oxygen, which prevents complete combustion and allows the disintegration of complex organic polymers into simpler molecular structures (Bridgwater, 2012; Manmai et al., 2020). Process parameters, such as temperature, heating rate, residence time, and feedstock characteristics, play an important role in the quantity and quality of biochar produced (Weber & Quicker, 2018). Low pyrolysis temperatures (300-500 °C) are favorable to the biochar preparation with increased yields and volatile matter, whereas high temperatures (500- 700 °C) are favorable to the production of more carbonized biochar with increased stability and surface area, as well as increased aromaticity (Kloss et al., 2012; Obey et al., 2022). The determination of the right pyrolysis procedures depends on where the biochar should be used and the physicochemical properties of the feedstock material (Demirbas, 2004; Gotore et al., 2022a).

Because agricultural deposits vary so much in their chemistry and structure, they don't react the same way to heat (Ronsse et al., 2013). Rice husk is a unique case; its high silica levels (15-20%) give rise to a biochar with special adsorptive controls that make it ideal for the cleaning up of contaminated environments (Shen, 2015). If the intention is better nutrient retention, rice straw is a better option because it contains more cellulose and hemicellulose (Yargicoglu et al., 2015). Corn residues are in the middle, having moderate lignin content and produce a balanced biochar which works well in normal farming (Mukome et al., 2013). Woods such as longan wood that are charred are loaded with lignin. This makes them produce a very stable, highly carbonized biochar, which is ideal for storing carbon for the long term (Crombie et al., 2013; Gotore et al., 2022b).

Despite the many studies done on individual feedstocks, it is still rare to find comprehensive studies comparing different materials under identical pyrolysis settings in the tropics (Enders et al., 2012). There is also the persistent challenge of making pyrolysis technology affordable and efficient to smallholder farmers (Sparrevik et al, 2013). This research addresses this lack of information by investigating four important agricultural wastes in northern Thailand. Using a modified barrel system, generate production efficiency and energy costs to determine what materials make the most sense economically. Completing this study was also the characterization of the chemical structure of the biochar through FTIR, which provides the best way for sustainable waste management that is specifically tailored to the needs of tropical agricultural settings.

2. Materials and methods

2.1 Study Location and Sample Collection

The study was conducted at the biochar production facility of Maejo University in Chiang Mai, Thailand (18.9°N, 99.0°E), utilizing raw agricultural materials gathered from fields across Chiang Rai province in northern Thailand during the post-harvest season of October to November 2025. Four agricultural residues were used on account of their abundance and disposal errors. rice husk (RH, 15 kg) from rice processing plants, rice straw (RS, 10 kg) after grain harvest, corn husk (CH, 10 kg) from corn processing and longan wood (LW, 15 kg) from pruned branches. These materials were manually collected, packed in used storage bags, and transported to the laboratory, where they were spread in a single layer under direct sunlight for 48 h to lower their moisture content. This is an important step to improve pyrolysis efficiency and biochar yield, as high moisture levels delay the thermal decomposition and increase energy consumption (Demirbas, 2004; Bridgwater, 2012).

2.2 Modified Barrel Pyrolysis System

2.2.1 Kiln Design and Construction

In the face of the disadvantages caused by traditional barrel kilns such as uneven heating, high smoky, and difficulty in controlling the entrance of oxygen, Olmius et al. (2016) made a plan to add a modified barrel pyrolysis kiln consisting of several key elements including a 200 liter steel barrel with removable screw-top lid, the external firewood combustion chamber, a vertical chimney of 150 cm high and 15 cm diameter, fuel supply mechanism including a used engine oil pool, controlled air blower for oxygen supply and insulation fiberglass to secure airtight sealing. This innovative formation assists in indirect heating, i.e., where the pyrolysis barrel is heated from the outside in the wood-fired combustion chamber, thus offering better temperature management and minimizing oxygen in. This innovative formation assists in indirect heating, i.e., in which the pyrolysis barrel is heated from outside the wood-fired combustion chamber, thus improving temperature management and reducing the oxygen input. An outline of the modified barrel kiln used to produce biochar is displayed in Figure 1.

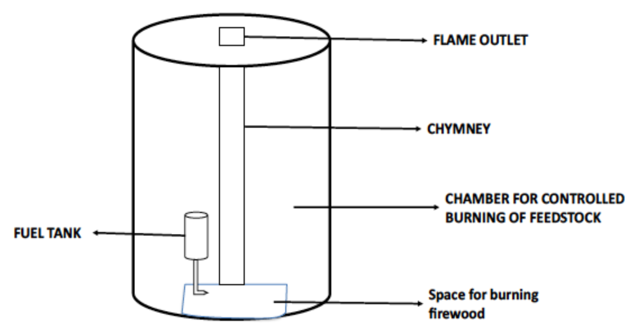


Figure 1: Outline of the modified barrel kiln used to produce biochar

2.3 Pyrolysis Procedure

2.3.1 Feedstock Loading

The dried agricultural remains (4.5-15 kg depending on bulk density) were loaded in the pyrolysis barrel with reduced compaction to facilitate air spaces, which allow the movement of volatile gas during pyrolysis (Ronsse et al., 2013). The lid of the barrel was based on a screw mechanism, and an insulation foam seal was used to create an anaerobic environment essential for pyrolysis (Weber & Quicker, 2018).

2.3.2 Combustion Initiation and Process Monitoring

The process of pyrolysis was initiated by the combustion of firewood in the external combustion chamber, and the process of combustion was monitored by a number of apparent indicators. Visual monitoring of flame color exiting the chimney were helpful as an actual indicator of the pyrolysis stage (Cornelissen et al., 2016), starting from light orange flame in the starting stage indicating combustion of volatile organic compounds (VOCs) and moisture release, to reddish flame in the middle stage representing mixed gas production from breaking down biomass, and finally to pale blue flame shows completion of pyrolysis with primary combustion of carbon monoxide and hydrogen. Process control was achieved by an electric air blower that provided a constant supply of oxygen into the combustion chamber to achieve a stable flame temperature. At the same time, used engine oil was drip-fed onto the burning wood at a controlled rate, in order to always produce the same amount of heat. Start and End times were logged for each of the experimental runs for process optimization analysis.

2.3.3 Process Duration

The time duration of running was from 2.5 to 3 hours, depending on the feedstock type and quantity. The process was completed if the flame of the chimney turned to a steady pale blue color, which was preserved for at least 10 minutes, indicating the exhaustion of the pyrolyzable volatile matter (Tripathi et al., 2016).

2.4 Biochar Collection and Storage

After process completion, the kiln was left to cool for at least 6-8 hours until room temperature (around 25-30 °C), as early opening of the kiln might expose hot biochar to atmospheric oxygen that could possibly lead to combustion and product loss (Lehmann and Joseph, 2015). Collection was done in an outside area, and precautions were taken, including surgical masks (N95 or equivalent) to avoid inhalation into the lungs of fine biochar particles and nitrile gloves to avoid direct skin contact with biochar. Collected biochar samples were transferred immediately into sealed plastic containers and accommodated in a dark, dry storage at room temperature for analysis.

The pyrolysis process was started by lighting firewood in the external combustion chamber, with the combustion process observed through several key indicators. Visual monitoring of flame color exiting the chimney helped as a actual indicator of the pyrolysis stage (Cornelissen et al., 2016), starting from light orange flame during the starting stage indicating combustion of volatile organic compounds (VOCs) and moisture release, to reddish flame in the middle stage representing mixed gas production from breaking down biomass, and finally to pale blue flame shows completion of pyrolysis with primary combustion of carbon monoxide and hydrogen. Process control was maintained through an electric air blower that ensured a constant oxygen supply to the combustion chamber for stable flame temperature. At the same time, used engine oil was gravity-fed onto the burning wood at a controlled drip rate to maintain consistent heat output. Start and End times were recorded for each experimental run for process optimization analysis.

2.5 Analytical Methods

2.5.1 Yield Determination

Biochar yield was calculated on a dry weight basis using the following equation (Enders et al., 2012):

$$\text{Biochar Yield (\%)} = \frac{\text{Mass of biochar produced}}{\text{Mass of dry feedstock}} \times 100$$

All masses were measured using a calibrated digital balance with ±0.01 kg precision.

2.5.2 Fourier Transform Infrared (FTIR) Spectroscopy

Chemical characterization of the biochar was taken care of by FTIR spectroscopy. Using Perkin Elmer Spectrum Two Spectrometer with the ATR method, 2-3 mg of ground samples with a wavenumber range of 4000-400 cm^{-1}. Each run comprised 32 scans at a resolution of 4 cm^{-1}. Once the raw data were obtained, the baseline was determined, and the results were obtained. Then determined the specific functional groups by comparison of the peaks with known literature (Keiluweit et al., 2010; Kloss et al., 2012).

2.6 Data Analysis

Descriptive statistics were calculated for biochar yields and energy inputs. FTIR spectra were analyzed for typical peaks corresponding to major functional groups. Comparative analysis was performed to assess differences in biochar properties among feedstock types. All measurements were conducted in triplicate to ensure reproducibility, although the presented data represent single experimental runs for each feedstock type.

3. Result and Discussion

3.1 Feedstock Characteristics and Thermochemical Implications

The four biomass residues, including rice husk (RH), corn husk (CH), rice straw (RS), and longan wood (LW), have shown different characteristics in terms of texture, packing behavior, and estimated mineral contents, which affect the effective pyrolysis severity of each feedstock inside the kiln/reactor. Characteristics of RH included moist and mineral-rich, RS and CH included fibrous and carbohydrate-dominant residues, and LW included dense woody residue (Table 1). These observable characteristics are important because the high-density low-void feedstock often will promote better retention of heat exposure and extended vacuum-solid contact time, which favors secondary char-forming reactions. In contrast, loose and porous residues provide for fast escape of the vapor and greater convective heat losses. Concurrently, factors such as mineral content (ash, specifically silica in RH) will influence thermal conductivity, catalytic cracking, and the percentage of "true carburizable organics," which leads to biochar with different yields, as well as different chemical composition and suitability for different applications.

This variability of the feedstock is highlighted in a recent study by Gholizadeh et al. (2024) in which the feedstock-type effects on biochar production are synthetically reviewed in terms of biochar yield, elemental composition, surface functional groups, and pore structure, and how feedstock effects interact with the influence of temperature and reactor configuration. At the component level, the decomposition sequence of lignocellulosic biomass is responsible for the mechanistic reasons for the differences observed. Initially, hemicellulose is decomposed because of its lower thermal stability, followed by cellulose and lignin is decomposed at a wider and generally higher range of temperatures. This contributes disproportionately to the solid fraction because the aromatic network is in favor of cross-linking and polycondensation rather than volatilization.

This sequence, as well as evidence for the volatile evolution, is strongly supported by the TG-FTIR mechanistic investigations, which prove that the volatiles from hemicellulose are released first, followed by those from cellulose and then lignin. An increase in severity leads to deoxygenation and polycondensation towards carbon aromatic structures (Chen et al., 2022). Rice husk must be considered a special case because of its high silica/ash content, and it is not just a minor modifier, but a defining characteristic for the identity and performance of char. A recent open-access review, aggregating information about the makeup of rice husk, shows rice husk consists of about 15-25% silica, with differences in the composition due to climate, variety, and geography, and that ash and silica have a significant influence on downstream behavior of the material (Hamidu et al., 2025).

The silica is usually in the form of amorphous silica-rich structures that are retained in the char, thereby creating mineral-carbon composite surfaces. This composite nature is beneficial in adsorption and immobilization applications; however, this composite nature makes the interpretation of "yield" more complex because mass yield may be affected by inorganic residue and may not represent fixed carbon yield unless proximate/ultimate analyses are presented.

Table 1. Characteristics of collected raw materials, including collection site descriptions and initial observations

S. No	Sample Name	Abbreviation	Weight	Collection Location	Remarks
1	Rice Husk	RH	15 kg	Chiang Rai	Wet material, piled in heaps at the field edge; high silica content expected
2	Corn Husk	CH	10 kg	Chiang Rai	Dumped at field corners post-processing; fibrous structure
3	Rice Straw	RS	10 kg	Chiang Rai	Post-harvest residue, left unused in fields; cellulose-rich
4	Longan Wood	LW	15 kg	Chiang Rai	Pruned branches, transported and dumped outside settlements; lignin-rich

3.2 Pyrolysis Process Parameters and Biochar Yield

Biochar yield showed a great variation among different feedstocks, varying from 31.1% to 43.3%, following the following order: LW (43.3%); RS (40.0%); CH (36.0%); RH (31.1%) (Table 2). This tends to be consistent with well-documented feedstock product relationships, for which more woody biomasses tend to produce more solid char. This is attributed to the tendency of lignin-derived fragments to easily repolymerize and aromatize, associated with the more extensive devolatilization of cellulose and hemicellulose components, which lead to larger vapor and liquid fractions. Gholizadeh et al. (2024) also highlight the critical importance of the biomass type as a key determinant of yield and physicochemical properties, such as pH, functional groups, and pore structure, incurring a need for comparisons between cross-feedstocks to be based on feedstock identity.

Table 2. Biochar yield calculated as a percentage of initial dry feedstock weight

S. No	Raw Material	Raw Material Weight (kg)	Pyrolysis Duration	Biochar Yield (kg)	Biochar Yield (%)	Firewood Efficiency (kg biochar/kg wood)
1	Longan Wood	15.0	3 h	6.5	43.3	0.325
2	Rice Straw	5.0	2 h 30 min	2.0	40.0	0.125
3	Corn Husk	5.0	3 h	1.8	36.0	0.106
4	Rice Husk	4.5	3 h	1.4	31.1	0.074

The higher yield for LW noted is a result of a combination of chemical and reactor physics. From a chemical point of view, lignin plays a large role in the creation of the solid response through the aromatic condensation pathways, which are preferred within the conditions of oxygen-deprived heating. From the physical perspective, LW's denser bulk density and lower void fraction will increase heat retention and contact time for vapor and solid, and will therefore increase the potential that condensable vapors will undergo secondary cracking and repolymerization on the char surface. This "secondary char" formation is often more evident with packed beds / traditional kilns, where the formation of vapors is forced to move through a hot char matrix before escaping.

The relatively high yield of rice straw (40.0%) indicates that, although the carbohydrate-rich composition of rice straw, the process conditions encouraged large amounts of char formation, which may be achieved with adequate residence time and internal heat distribution to allow for partial secondary charring. The intermediate yield of corn husk (36.0%) is correlated with the fibrous and low-density biomass of corn husk that can devolatilize efficiently (leading to more vapor formation) and can have greater heat losses in the batch process. The smallest amount of rice husk (31.1%) corresponds to the lower content of carbonizable organics in relation to the silica-rich ash and possible ash-induced changes in thermal behavior, as the composition review of rice husk displays a good content of ash/silica, as well as ranges supporting this interpretation.

3.3 Yield Performance and Energy Efficiency Analysis

The efficiency metric for firewood showed a great variation (0.074-0.325 kg biochar/kg wood) with preference to LW and disadvantage to RH (Sparrevik et al., 2013). Mechanistically, these types of differences are normally caused by: (i) the need for moisture removal (latent heat penalty), (ii) the differences in packing/heat retention (radiative/convective losses), and (iii) the efficiency of the secondary reactions through converting vapors to additional char. This high moisture content and ash content of RH is likely to increase the heat demand without a proportional increase of carbon retention, which is good in supporting heat utilization (Keiluweit et al., 2010). Notably, modern evaluations reflect the net climate and sustainability results of pyrolysis to biochar systems are also highly complicated by energy management and most layouts (e.g., are pyrolysis gases recovered for process heat. Zhu et al. (2022) expressed that LCA on agro-residue biochar production suggests that direct comparisons between studies are difficult because of variable functional unit and boundary, but energy integration and technology choice have a significant influence on net carbon performance.

Longan wood had the highest biochar yield at 43.3%, and this result could be explained by the high lignin content (25-35%) and high mass input (15 kg), enabling better heat retention (Crombie et al. 2013). This was followed by rice straw with a yield of 40.0%, which went through a faster thermal decomposition due to its lower bulk density (Yargicoglu et al., 2015). Corn husk obtained a yield of 36.0% due to the good volatile gas release through the fiber structure (Mukome et al., 2013). In contrast, rice husk gave the least yield of 31.1% with the longest processing time (3 hours) and high firewood consumption (19 kg). This decreased yield is explained by its high silica content (15-20%), which increases the inorganic ash fraction at the expense of the organic carbon available for biochar production (Shen, 2015). Comparison of raw material, firewood use, and biochar yield is presented in Figure 2.

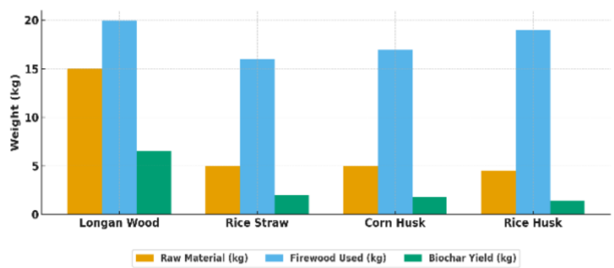


Figure 2. Comparison of raw material, firewood use, and biochar yield

3.4 FTIR Spectroscopic Evidence for Structural Transformation

Fourier-transform infrared (FTIR) spectroscopy proved the successful conversion from biomass into aromatized carbon structures on all biochar and also showed the feedstock-specific mineral and functional group characteristics (Figure 3). It is a good idea to match the assignment of bands with known FTIR schemes. A recent adsorption investigation of rice husk provides an explicit attribution of several characteristic bands in the vibrations of rice husk: the band at ~3430 cm^{-1} to -OH stretching, at ~2920 cm^{-1} to aliphatic C-H stretching, the band at ~1640 cm^{-1} to C=C stretching, and, interestingly, the band at ~1090/1050 cm^{-1} to Si-O-Si asymmetric stretching. This is in direct support of the attribution of silica at around 1050 cm^{-1} for that generated from rice husks (Lu et al., 2024).

3.3.1 Rice Husk Biochar (RH)

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3.3.2 Rice Straw Biochar (RS)

Figure 4 depicts that the rice straw contains an intricate composition due to the presence of cellulosic (C-O-C) and mineral (Si-O-Si) peaks at around 1030 cm^{-1}. The large aromatic peak at 1630 cm^{-1} indicates critical aromatization in the course of pyrolysis and its impact on biochar stability and its ability to trap carbon (Lehmann and Joseph, 2015). The aromatic band can be seen at the area of around 1630 cm^{-1}, and the existence of oxygen-functional groups in the areas of 1000-1100 cm^{-1}, which suggests that rice straw is moderately aromatized without loss of oxygen functionality on the surface. This finding corresponds to the mechanistic perception that the severity of the increase in severity results in the deoxygenation of the oxygenated groups, but the remaining -OH/-COOH/phenolic functionalities might remain, leading to cation exchange and retention of nutrients in soil works.

The strong step towards developing a better indicator of aromaticity based on FTIR data is to quantify the aromaticity, but not merely describe it qualitatively: a peer-reviewed method determines an aromaticity index, the ratio of the integrated areas of the peaks around 1630 cm^{-1} to the ones around 2929 cm^{-1} (C=C relative to the aliphatic C-C/C-H signatures). The fact that this index is reported, even in the form of relative values in various samples, makes the discussion more rigorous and allows making comparisons that are defensible (de Oliveira et al., 2024).

3.3.3 Corn Husk Biochar (CH)

The presence of oxygen-binding functional groups (Figure 5) at the rate of about 3400 cm^{-1} and1050 cm^{-1} shows that corn husk biochar could be able to retain its surface reactivity, which is useful in nutrient retention in soil use (Mukame et al., 2013). The aromatic peak (1550-1600 cm^{-1}) confirms the stability of carbon, hence, qualifying it to be used as a long-term carbon sequestration. The -OH (~3400 cm^{-1}) and the aromatic-region (~1550-1600 cm^{-1})-peaks of the corn husk biochar are distinct, which means that the biochar is a composite composition containing an aromatic structure with a rather more polar surface at the cost of surface oxygenated functional groups. Mechanistically, the high persistence of the -OH groups may be a sign of either lower effective severity, lower effective time at high temperature, or even postproduction oxidation at low temperature or storage. Since oxygenated groups would tend to diminish with severity due to dehydration and decarboxylation, the FTIR pattern of the corn husk biochar demonstrates that the biochar formed can be relatively more active (distinctly high wettability and potentially high nutrient interaction), but not always the most stable type of carbon.

3.3.4 Longan wood biochar (LW)

The existence of oxygen-containing functional groups that are signified in Figure 6 (~3400 cm^{-1} and -1050 cm^{-1}) shows that the corn husk biochar does not lose surface activity; this is beneficial in terms of nutrient retention in soil uses (Mukame et al., 2013). Aromatic peak (1550-1600 cm^{-1}) proves that carbon is not unstable, and it can be used in long-term carbon sequestration. LW is highly aromatic (in the range of 16001650 cm^{-1}) and less aliphatic (in the range of 2900 cm^{-1}), which is also in line with the aromatization and polycondensation of the solid phase. This observation corresponds to the current evidence on carbon permanence, which states that the production conditions of higher temperature or more severe conditions lead to increased condensed aromatic structure with less alkylation, which is associated with increased carbon stability. Although FTIR cannot fully determine permanence, the aromatic preeminence of LW is directionally consistent with stability measures emphasizing aromatic condensation, which can be substantiated using both elemental H/C and O/C ratios.

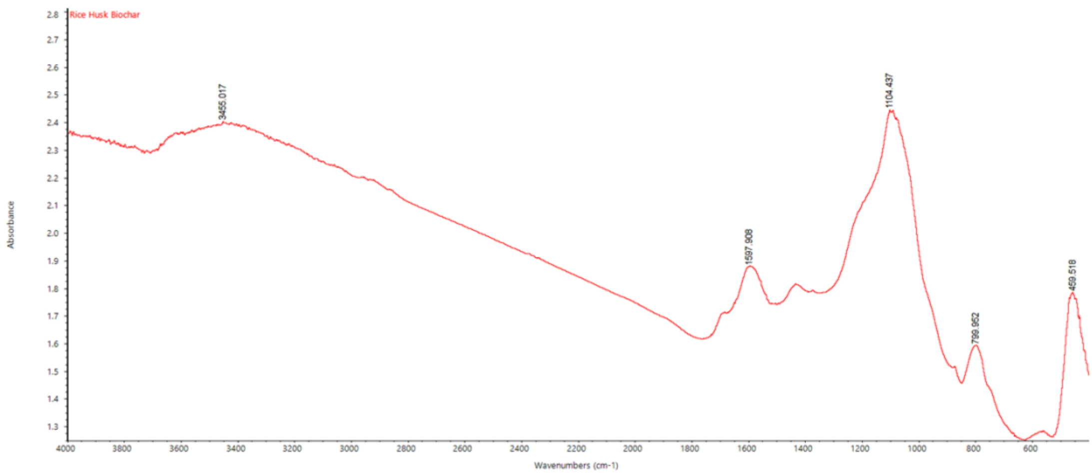

Figure 3. FTIR Spectrum of Rice Husk Biochar

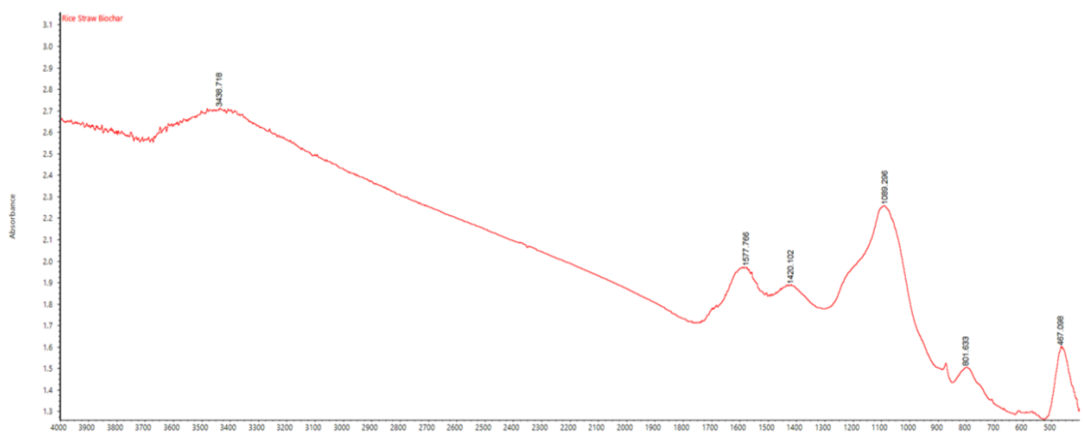

Figure 4. FTIR Spectrum of Rice Straw Biochar

Figure 5. FTIR spectrum of Corn husk biochar

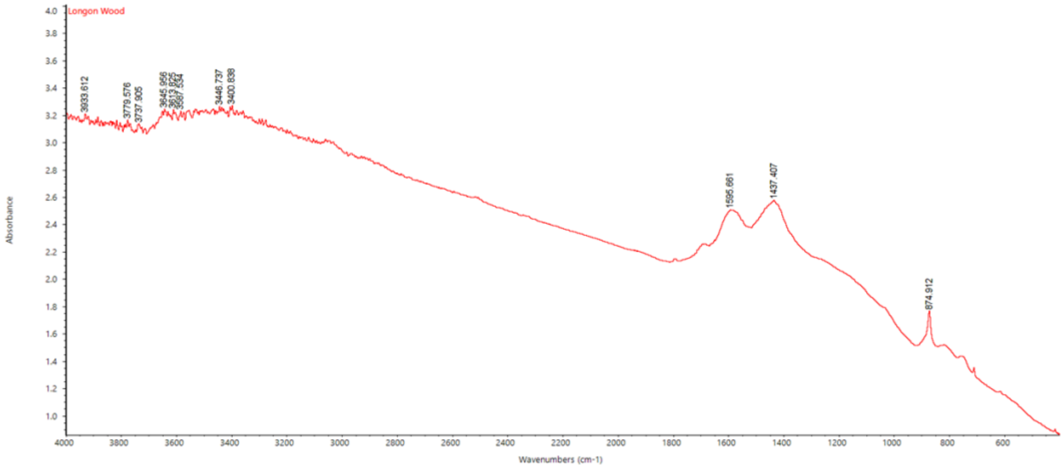

Figure 6. FTIR Spectrum of Longon Wood Biochar

3.4 Comparative Functional-Group Interpretation and Stability Implications

In all the samples of biochar, the presence of peaks in the aromatic region (around 1590-1650 cm^{-1}) is indicative of the presence of formalin carbon matrices. However, the levels of aromatization and relative prominence of mineral-associated bands show significant variability according to the feedstock, which makes it easier to select biochar for specific applications. Rice husk is described as a silica-dominant mineral-carbon composite, and lignin waste is known for its highly aromatized carbon structure. Rice straw and corn husk fall midway in having a richer number of residual oxygen functionalities. Recent literature on the stability of carbon stresses the need not rely too much on a single metric. A comparative analysis published in Science of the Total Environment highlights the feedstock influence on carbon structural stability and presents some of the types of analysis methods to examine structural stability that are applicable to carbon crediting and permanence inference. In the context of the above, it seems that the conclusions result from a balanced result showing the strength of the aromatic condensation found by LW, which may suggest high permanence, while the silica signature found by RH suggests that a greater number of pathways of mediation and mineral contributions are involved that are not solely carbon adsorption.

When the yield, firewood efficiency, and the FTIR chemistry are considered as a group, a hierarchy of feedstock performance can be seen coherently. LW seems to be ideally suited for carbon retention-oriented applications, as it has a combination of the best mass yield with the best fuelwood efficiency and the best FTIR signature (most pronounced aromatic). RS and CH exhibit intermediate yielding and retention of oxygenated surface groups that may be beneficial for soil amendment use, e.g., nutrient interaction and wettability, although their persistence should preferably be supported by elemental ratios and oxidation-resistance evaluation tests. RH, though being less efficient in this specific production configuration (with the lowest yield and efficiency in terms of fuelwood), is very characteristic from a chemical point of view. Silica-rich biochar can be useful in remediation applications in which silicate-associated immobilization or mineral-carbon composite adsorption is of paramount importance, which is like the recent remediation applications explicitly using activated silicon in rice husk biochar for cadmium immobilization (Zhu et al., 2022). From a systems point of view, the life cycle assessment (LCA) is a useful indicator of how pyrolysis design and energy management can have a substantial impact on a system's sustainability performance, especially for lower-efficiency feedstocks, by incorporating the use of process heat recovery or coproduct utilization instead of relying on external energy inputs.

4. Conclusion

This study addresses agricultural residue burning in Thailand, particularly rice straw and husk, which causes air pollution while wasting resources. It evaluates biochar production from Northern Thailand residues using a modified 200-L barrel pyrolysis system with improved temperature control via external heating, air blower, and chimney indicator. Feedstocks were sun-dried and pyrolyzed in ~2.5–3 h batches, with completion shown by pale-blue chimney flame. Biochar yield was different depending on the feedstock: longan wood (43.3%) > rice straw (40.0%) > corn husk (36.0%) > rice husk (31.1%), which was related to lignocellulosic composition. Rice husk, having high silica content, decreased carburizable organics but brought mineral carbon characteristics. Production efficiency varied depending on the feedstock, with 0.074 to 0.325 kg biochar per kg wood and 19 kg firewood being obtained for rice husk, with the lowest efficiency and the longest processing time (3 h). FTIR-ATR spectra affirmed the formation of aromatized carbon (1590-1650 cm^{-1}), whereas showed feedstock characteristic: rice husk presented silica character (1090/1050 cm^{-1}) in the presence of -OH (3430 cm^{-1}), and C-H (2920 cm^{-1}); rice straw and corn husk still contained more oxygenated functional group (1000-1100 cm^{-1}; -OH at 3400 cm^{-1}); longan wood showed the most aromaticity Based on yield, efficiency and FTIR analysis, longan wood biochar is suitable for carbon sequestration, rice straw and corn husk biochar for soil amendment, and rice husk biochar for remediation. The modified barrel kiln is the appropriate technology for the local production of biochar for tropical smallholder systems.

Acknowledgement

The authors gratefully acknowledge the financial support provided by the Southeast Asian Regional Center for Graduate Study and Research in Agriculture (SEARCA) under the University Consortium (UC) Seed Fund for Collaborative Research Grant (Grant No. OD25-891). The authors sincerely thank SEARCA for funding this research initiative and for their

commitment to advancing sustainable agricultural innovation and environmental solutions in the region.

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