CONCURRENT PRODUCTION OF BIOCHAR AND LIQUID SMOKE FROM COCOA POD HUSK FOR SUSTAINABLE AGRO-WASTE VALORIZATION

Muhammad Zulhajj Khan, G.K., Hanis Haziqah, I., Sannasi, P.*, Siti Nuurul Huda, M.A., and Ch'ng, H.Y.
Faculty of Agro-Based Industry, Universiti Malaysia Kelantan Jeli Campus, 17600 Jeli, Kelantan, Malaysia
**Corresponding author: palsan.abdullah@umk.edu.my*

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ABSTRACT – *Cocoa pod husk (CPH), a major by-product of cocoa production, remains largely underutilized, posing environmental and economic challenges for smallholder farmers. This study investigates the concurrent conversion of CPH into biochar and liquid smoke through slow pyrolysis and condensation, offering a dual solution for waste management and value addition. The sustainable valorization of CPH was assessed by analyzing the process temperature profile, yield, and product characteristics. Five experimental trials were conducted using a custom-designed carbonization drum, with CPH sourced from Machang and Bagan Datuk Malaysian Cocoa Board stations. The process temperature ranged from 44.33°C to 358.47°C across three drum zones (bottom, middle, top) over 180 minutes. The recommended temperature range for complete carbonization is 350-450 °C. The trials successfully co-produced biochar and liquid smoke, with average yields of 43.71 ± 2.77% (biochar), 46.36 ± 8.89% (raw liquid smoke), and 7.78% (purified liquid smoke). Biochar exhibited an alkaline pH (10.1-10.3), low moisture content (4.64-7.42%), low ash content (5.5-5.8%), moderate volatile matter (19.7-33.08%), and high fixed carbon (54-69.28%), making it suitable for soil amendment or activated carbon precursor. The results indicated that larger particle sizes (> 1 mm) produced biochar with higher fixed carbon (69.28%) with lower volatile matter (20.55 ± 2.07%),and moisture content (4.64 ± 0.27%). While, smaller particles (≤ 125 µm) retain higher moisture (7.42 ± 0.15%) and volatile matter (33.08 ± 1.07%), but had reduced fixed carbon (54%). Purified liquid smoke (pH 8.9-9.63) obtained through fractional distillation (70-110°C), demonstrated potential as a soil enhancer, germination stimulant, biopesticide, and biochar activation agent, with notable antioxidant properties. Temperature variations significantly influenced product yield and characteristics. These findings highlight CPH as a viable feedstock for biochar and liquid smoke production, supporting sustainable agriculture, climate mitigation, and biomass-derived product development. Further research on economic feasibility is needed to facilitate implementation at cocoa farms.*

Keywords: Biochar, carbonization, climate change, condensation, liquid smoke

INTRODUCTION

Agricultural waste or agro-waste are non-product outputs, residuals, or left-overs resulting from the post-harvest handling of cultivated crops, as well as the processing, and production activities of agricultural products from agro-based industries. In Malaysia, the agricultural sector covers of a diverse range of agro-commodity crops, broadly categorized into plantation crops, food crops, and industrial crops. Plantation crops and their respective planted areas include oil palm (5.67 million hectares), rubber (1.14 million ha), pepper (8,000 ha), cocoa (6,000 ha), and kenaf (800 ha) (DOSM, 2023). Although the area under cocoa cultivation has declined significantly, ongoing efforts are being made to revitalize cocoa farming in Malaysia to reduce reliance on imported beans. As of 2023, there are 5,452 smallholders involved in cocoa (Khairul Bariah *et al.,* 2024).

This study focuses on the utilization of cocoa pod husk (CPH), the main agro-waste left on the farm after harvesting and primary processing of cocoa to obtain fresh beans. Figueroa *et al.* (2019) indicated that cocoa beans account for only about 30% of the cocoa fruit, while the remaining fractions, such as the CPH and the mucilage or pulp, are treated as waste by-products. Rozita *et al.* (2022) reported that the CPH left in the field contributes to pest and disease problems. According to de Souza Vandenberghe *et al.* (2022), CPH structurally constitutes 60-70% of the dry base weight of the cocoa pod, and is rich in cellulose (35%), hemicellulose (11%), lignin (14.6%), ash (9.1%), pectin (6.1%), protein (5.9%), and minerals (0.32% calcium, 3.18% potassium, 0.15% phosphorous). Fresh CPH has a high moisture content, making it susceptible to microbial spoilage and degradation. In the context of sustainable development and circular economy principles, valorizing CPH into added-value product precursors presents both environmental and economic opportunities.

Pyrolysis, or carbonization, of carbonaceous material such as agro-waste biomass at varying temperature ranges can produce biochar. Biochar, a porous, carbon enriched material feedstock, has garnered significant global interest due to its wide-ranging co-benefits. These include improving the physical, chemical, and biological properties of soil, supporting better plant growth and increased crop yields, serving as a component of environmental technologies such as water filtration, bioremediation, pollutant removal, mitigating climate impacts through carbon sequestration, acting as a precursor for the development of new biochar-infused products, providing a means for socio-economic empowerment of communities, and offering new economic opportunities through tradable carbon credits (Yu *et al.,* 2024; Sannasi *et al.,* 2024; Azrine *et al.,* 2023; Seow *et al.,* 2022; Lehmann *et al.,* 2021). Nevertheless, the production of biochar depends on several factors, including feedstock, process parameters (temperature, residence time, particle size, moisture, oxygen), conversion method, tools and scale (Azrine *et al.,* 2023; Rozita *et al.,* 2022). Liquid smoke, also referred to as pyroligneous acid, is a by-product of condensable gases produced during pyrolysis or carbonization. Like biochar, its production and properties are influenced by factors such as feedstock composition, process conditions, and conversion methods (Hagner *et al.,* 2020). Liquid smoke has been shown to be beneficial in agricultural practices, not only as a soil conditioner, but also as a herbicide, insecticide, and fungicide (Wibowo *et al.,* 2023). The feasibility of agro-waste conversion can be enhanced if added-value applications for all resulting product fractions are developed.

While research on biochar and liquid smoke production is abundant in the literature, there is a lack of discourse on the simultaneous production of biochar and liquid smoke from CPH *in situ*. Establishing an efficient process flow for producing both biochar and liquid smoke from CPH could offer economic opportunities for farmers, entrepreneurs, and industries involved in cocoa production potentially generating new income and boosting rural development. The primary aim of this study is to explore the feasibility of concurrently producing biochar and liquid smoke from CPH using an environmentally friendly carbonization kiln setup.

MATERIALS AND METHODS

Feedstock preparation

The study was conducted at Universiti Malaysia Kelantan (UMK) Jeli Campus, Kelantan. The feedstock consisted of CPH sourced from the Machang and Bagan Datuk Malaysian Cocoa Board stations (Figure 1). Prior to processing, the CPH was dried in a rotary dryer, sun-dried, or oven dried (Model FAC-350H).

Figure 1: Collected CPH.

Process conditions and product separation

The carbonization kiln setup is shown in Figure 2.

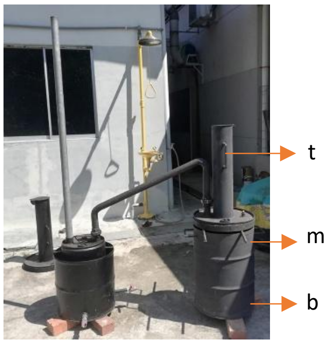

Figure 2: Carbonization kiln setup. Arrows indicate the temperature measurement points; t: top, m: middle, and b: bottom.

The unit is a custom-designed top lit up draft (TLUD) carbonization drum. The primary drum is used to burn waste wood as fuel, which will indirectly heat up to carbonize the CPH (of known weight, kg) contained in the closed carbonization reactor placed inside the drum. The carbonization reactor is fitted with a gas outlet pipe that directs volatile gases into the condenser drum unit via an inclined pipe. The condenser drum unit is immersed in water to facilitate further condensation, with liquid smoke from the condensable gases accumulating inside. A flare pipe safely burns excess or non-condensable gases (mainly CO, CH_4, H_2) preventing the release of excessive smoke and pollutants. Temperature during the pyrolysis process is recorded every 10 min for 180 min using a Digital IR Thermometer (Habotest HT651D) at the top (t), middle (m), and bottom (b) sections of the primary carbonization drum.

At the end of the process, the carbonization drum was left to cool. The carbonized CPH (as biochar) was then removed and weighed (kg). Biochar yield (%) was calculated by comparing the mass difference (kg) between the initial CPH and the biochar produced. The raw liquid smoke inside the condenser drum was drained into collection bottles. The yield (%) of raw liquid smoke was determined by comparing the mass difference (kg) between the initial CPH and the mass of raw liquid smoke produced (Ifa, 2021). The collection bottles were allowed to stand for 2 weeks to enable phase separation through sedimentation. The top layer was then carefully strained using filter cloth to remove the remaining tar and particulate matter.

Fractional distillation of liquid smoke

The filtered liquid smoke solution (300 mL per batch) was used for fractional distillation (Yulistiani *et al.,* 2020; Pires *et al.,* 2019). The fractional distillation setup consisted of a distillation flask, fractionating column, thermometer, condenser, receiving flask, and heating mantle. Distillates were collected at 70-90 ºC (F1) and 90-100 ºC (F2), over 180 min. The yield (%) of purified liquid smoke was calculated by comparing the initial volume (mL) of filtered liquid smoke with the volume (mL) of the resulting distillate fractions.

Product characterization

The obtained CPH derived biochar was first washed, oven-dried (Model FAC-350H), ground, and fractionated by manual sieving (Retsch Test Sieves). The sieves were stacked in descending mesh order, with the collecting pan at the bottom, followed by mesh sizees #230, #120, #60, #35, and #18. The retained fractions (x) were categorized into five particle size ranges: I ($x > 1$ mm), II ($500 < x \leq 1$ mm), III ($250 < x \leq 500$ µm), IV ($125 < x \leq 250$ µm), and V ($63 < x \leq 125$ µm). These fractions were subsequently subjected to characterization. The following product characterizations were performed: pH of biochar by method of Abdolali *et al.* (2015), moisture content (%) using a moisture analyzer (AND MX-50), ash content (%), and volatile matter (%) using a muffle furnace (Protherm Furnace ECO series) as described by Adekanye *et al.* (2022) and Antwi-Boasiako & Glalah (2021). Fixed carbon (%) was calculated by subtracting the sum of moisture content, volatile matter, and ash content from 100%. For liquid smoke, its color was noted, pH was measured, acid content (%) was determined using the titration method (Prianto *et al.,* 2020). In this method, 1 mL of liquid smoke was weighed carefully and then mixed with 100 mL of distilled water. Three drops of phenolphthalein indicator were added and homogenized. The solution was then titrated with 0.1 N NaOH until the solution shifted from clear yellow to yellowish-brown color. The acid content was expressed as percent acetic acid, calcualted using the formula: Total acid (%) = $[V \times N \times MW\_ac) / (w \times 1000] \times 100\%$, where V is the NaOH volume (mL), N is the normality of NaOH, MW_ac is the molecular weight of acetic acid (60.05 g/mol), and w is the sample weight. Liquid smoke density wsa determined using a pycnometer (Xu, 2022).

RESULTS AND DISCUSSIONS

Process conditions

The mean temperature trend of the primary carbonization drum is presented in Figure 3. The data represents the temperature readings from the top, middle, and bottom sections of the drum over 180 min, reflecting the vertical heat transfer dynamics within the system.

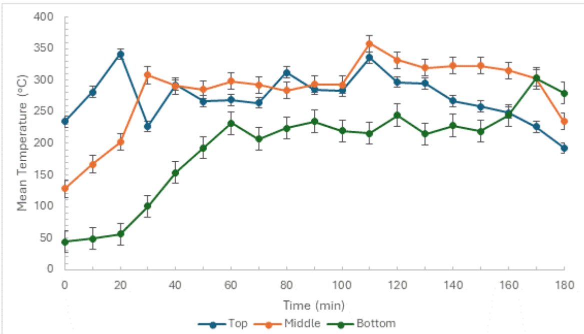

Figure 3: Temperature trend of primary carbonization drum (readings of mean ± SD).

Initially, the top region exhibited a relatively higher average temperature (234.27 °C), while the middle (128 °C) and bottom (44.33 °C) layers were lower, indicating that heat concentration was primarily localized at the upper part, as expected in a top lit up draft (TLUD) system. Within the first 30 min, both the top and middle temperatures rose steadily, with the top peaking at 341.53 °C at 20 min before dropping to 227.2 °C at 30 min. This drop suggests a transient shift in heat distribution, due to thermal draft migration downward after the consumption of waste firewood. After 30 min, both the middle and bottom temperatures increased steadily. The middle zone peaked at 110 min (358.47 °C), and remained above 300 °C, while the bottom section showed a consistent rise, reaching a peak of 303.27 °C at 170 min. This delayed response reflects the gradual penetration of heat to carbonize the CPH feedstock in the carbonization reactor. As reviewed by Cahyanti *et al.* (2020) from Tumuluru *et al.* (2011), biomass breakdown occurs in three temperature intervals. First, from 50 °C to 150 °C (non-reactive drying), moisture is driven off, and the material shrinks, with lignin beginning to soften near 150 °C. Between 150 °C and 200 °C (reactive drying), hydrogen–carbon bonds break, releasing lipophilic compounds (e.g., fatty acids, sterols, terpenes) and depolymerizing hemicellulose into shorter, condensed polymers. Finally, from 200 °C to 300 °C (destructive drying), devolatilization and carbonization take place, fully degrading hemicellulose and partially breaking down cellulose and lignin. Lignin begins to pyrolyze between 150-900 °C, hemicellulose between 220-315 °C, and cellulose between 315-400 °C. The convergence of temperature values across all three layers after 100 min indicates a more uniform thermal environment. By 180 min, the top, middle, and bottom regions recorded temperatures of 192.67 °C, 234.87 °C, and 279.67 °C, respectively. Notably, the bottom temperature eventually surpassed the top, indicating the completion of the process. Based on the observed temperature trend, the carbonization of CPH can be best described as mild (low-temperature) pyrolysis, occurring within the 250-450 °C range with long vapor-residence times (Jenkins *et al.,* 2016).

Product yield and characterizations

The carbonization process produced both biochar and liquid smoke concurrently (Figure 4).

Figure 4: Biochar and raw liquid smoke from CPH.

The biochar yield from the 5 sample runs is presented in Table 1. A total of 15.1 kg of CPH was converted into 6.6 kg biochar, resulting in an average yield of 43.71 ± 2.77%. Quansah (2021) obtained a biochar yield of 33.4% (82.5 kg) from the conversion of 245.5 kg CPH by using the Kon-tiki kiln. While Ogo *et al.* (2025) reported a CPH biochar yield in the range of 35%-55% at final temperatures of 357.92 ºC and 331.29 ºC, respectively. The temperature range was similar and the yield was comparable to the present study. The mass reduction was attributed to moisture removal, as well as breakdown and volatilization of organic matter.

Table 1: Biochar yield from CPH

Sample #	Initial weight of CPH (kg)	Biochar weight (kg)	Yield (%)
1	2.6	1.1	42.31
2	2.6	1.4	53.85
3	2.3	1.1	47.83
4	4.1	1.6	39.02
5	3.5	1.4	40.00

The biochar was sorted based on its particle size (Table 2). It exhibited an alkaline pH (10.1-10.3), low moisture content (4.64-7.42%), moderate volatile matter (19.7-33.08%), low ash content (5.5-5.8%), and high fixed carbon (54-69.28%). Finer biochar particles tend to retain more moisture, likely due to their increased surface area and greater exposure to the external environment (Kumar, 2021). Samples of different particle sizes are suitable for various applications, including soil additives, co-composting, pellets, briquettes, adsorbent, and precursors for activated carbon, among others. The values obtained are consistent with those reported in the literature. These characteristics make it suitable for use as soil amendment to address acidic conditions (Bolan *et. al.,* 2023).

Table 2: Biochar product characterization

Sample size	pH	Moisture content (%)	Volatile matter (%)	Ash content (%)	Fixed C (%)
I	10.1	4.64 ± 0.27	20.55 ± 2.07	5.5 ± 0.67	69.28
II	10.2	5.63 ± 0.39	19.70 ± 1.84	5.8 ± 0.49	68.87
III	10.2	6.60 ± 0.17	25.74 ± 1.83	5.8 ± 1.48	61.86
IV	10.3	6.74 ± 0.12	22.76 ± 3.11	5.5 ± 0.27	65.00
V	10.1	7.42 ± 0.15	33.08 ± 1.07	5.5 ± 0.55	54.00

Note: I: $x > 1$ mm, II: $500 < x \leq 1$ mm, III: $250 < x \leq 500$ µm, IV: $125 < x \leq 250$ µm, V: $63 < x \leq 125$ µm

Biochar, when used as a soil enhancer, offers significant benefits to smallholders by promoting favorable crop growth. These benefits stem from improved water retention, pH stabilization, nutrient and ionic balance, and overall soil structure enhancement. Characterization studies of biochar produced from CPH by Rozita *et al.* (2022) have revealed increased nutrient content, including total nitrogen (3.35%), phosphorus (0.364%), potassium (9.8%), calcium (0.78%), and magnesium (0.53%), compared to raw CPH. The addition of CPH-based biochar to soil can help address issues such as poor soil conditions caused by physico-biological-chemical imbalances, nutrient loss due to runoff or insufficient fertilization, and poor water retention. By converting CPH into biochar and liquid smoke for use as soil amendments, the process supports sustainable cocoa cultivation by returning essential carbon and minerals to the soil.

The liquid smoke yield from the 5 sample runs is presented in Table 3.

Table 3: Liquid smoke yield from CPH

Sample #	Initial weight of CPH (kg)	Liquid smoke weight (kg)	Yield (%)
1	2.6	0.5	19.23
2	2.6	1.3	50.00
3	2.3	1.6	69.57
4	4.1	2.4	58.54
5	3.5	1.2	34.29

In total, 15.1 kg of CPH produced 7 kg of liquid smoke, resulting in an average yield of 46.36 ± 8.89%. Both biochar and liquid smoke yield vary depending on factors such as temperature, vapor phase residence time, heating rate, heat dispersion homogeneity, and the chemical composition of the biomass (Batista & Gomes, 2021). Slow, low temperature pyrolysis with long vapor-residence times favors char (~35%) and gases (~35%) as the major products, followed by bio-oil (~30%) (Jenkins *et al.,* 2016). For liquid smoke, the containment and collection of condensable gases in the condenser drum are critical, while non-condensable gases are emitted through the flare piping.

Table 4 presents the characteristics of raw liquid smoke, F1, and F2.

Table 4: Characteristics of CPH derived liquid smoke

Sample	**Appearance**	**Density (g/cm^3)**	**pH**	**Acid content (%)**
Raw liquid smoke	Dark, oily	na	8.9	na
F1	Brown	0.98	9.6	3.27 ± 0.15
F2	Light brown	0.97	9.3	1.60 ± 0.10

F1: distillation fraction collected at 70-90 ºC.
F2: distillation fraction collected at 90-100 ºC.

F2 was lighter in color and density compared to F1 (Figure 5).

Figure 5: F1 (right) and F2 (left)

All samples exhibited basic properties, indicating that basic compounds such as phenolic and nitrogenous molecules, were retained in the fractions. This is advantageous for addressing acidic soil issues. F1 exhibited a higher acid level compared to F2, though the difference was not significant ($p \geq 0.05$). The lower content of acid fractions, such as acetic acid and formic acid, may reduce corrosiveness in specific applications involving storage tanks, pipelines, and processing equipment.

The raw liquid smoke, which contains tar, was collected until no more liquid emerged. At this point, non-condensable gases, including CO, CO_2, and CH_4, were released into the atmosphere as described by Ifa *et al.* (2018). In their study on cashew nutshell, they reported a 53.4% liquid smoke yield at 400 ºC, composed of phenol (36.6%), carbonyl (1.7%), and acid (18.8%). At the end of the distillation process, the combined fractions (F1 and F2) yield were 7.78%, resulting in 1.2 L of purified liquid smoke. Producing a high-quality distillate requires primary and secondary condensation, fractionation, and further separation using affinity columns (Pires *et al.,* 2019).

To enhance feasibility, future efforts should focus on product development of added-value liquid fractions for use as soil enhancers, germination stimulants, biopesticides, biochar activation agents, or antioxidants. The outcome of this study align well with the strategy outlined in the National Biomass Action Plan (NBAP) 2023-2030 (Ministry of Plantation and Commodities, 2023) for (i) potential utilization of CPH as biochar, activated carbon, bioorganic fertilizers, and soil enrichment media, and (ii) viewing it as entry point activities to encourage cocoa smallholders' participation in the circular economy. In reviewing the production process, traditional biochar production methods, such as soil pits and open drum burning, are inexpensive but slow, resulting in low biochar yields. These methods also release greenhouse gases (CH_4, CO_2), which contribute to air pollution and health concerns (Pandit *et al.,* 2017). The next step is to introduce this carbonization kiln setup to smallholders, with the potential for adoption to produce both biochar and liquid smoke.

CONCLUSIONS

The findings from this study demonstrate the practical feasibility of concurrently converting cocoa pod husk (CPH) into biochar and liquid smoke using a customized carbonization kiln. On average, the process yielded 43.71% biochar and 46.36% liquid smoke, confirming its efficiency as a dual-product valorization pathway. The biochar exhibited alkaline pH, low ash and moisture content, and high fixed carbon, making it suitable for soil improvement. Notably, particle size greatly influenced biochar quality: larger particles (> 1 mm) yielded higher fixed carbon with lower moisture and volatile matter, while finer particles (≤ 125 µm) retained more volatiles and moisture but had reduced carbon stability. The purified liquid smoke fractions, characterized by basic pH, showed potential applications as soil enhancers. Process temperature was key determinant of yield and product characteristics. Collectively, these findings highlight CPH as a viable feedstock for sustainable biomass valorization, supporting climate mitigation, soil rehabilitation, and the development of bio-based agricultural inputs. Future studies should assess the economic feasibility and scalability of this approach to facilitate adoption among cocoa smallholders.

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