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Cocoa Agro-Industry Development Based on Pyrolysis Technology with Cocoa Liquid Smoke, Biochar and Bio-Oil Product

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Abstract: This study aims to analyze the utilization of cocoa husk through fermentation and pyrolysis processes into three main derivative products, namely liquid smoke, charcoal (biochar), and bio-oil. Cocoa husk was collected from cocoa fruit in Central Mamuju Regency, West Sulawesi Province. Before the pyrolysis process, the cocoa husk was fermented to reduce water content, increase homogeneity, and reduce interfering compounds such as complex lignin. Fermentation also increases pyrolysis efficiency by opening the cellulose and hemicellulose structures. After fermentation, the cocoa husk was dried and fed into a pyrolysis reactor with combustion temperatures of 112, 212, 312, 412, and 512°C for 5 hours. During the pyrolysis process, the cocoa husk decomposed into three main phases: the solid phase produced biochar, the liquid phase produced bio-oil, and the gas formed during pyrolysis was condensed into liquid smoke. The experimental results showed that temperature plays an important role in determining the amount of liquid smoke product produced. A temperature of 212°C is considered the optimum temperature to obtain the highest liquid smoke yield. This process not only increases the efficiency of cocoa shell waste utilization, but also produces products that can be applied in various industries, such as filtration, air treatment, alternative energy, and preservation. SEM and FTIR analysis show the potential and value of the resulting products in accordance with the principles of sustainable agro-industrial development and circular bioeconomy.

Keywords: *Agro-industry, cocoa husk, cocoa pod, liquid smoke, pyrolysis.*

1. Introduction

Indonesia, as the third-largest cocoa producer in the world after Ghana and Côte d'Ivoire, plays a vital role in the global cocoa market and significantly contributes to the national economy by providing employment, income, and foreign exchange (Fahmid et al., 2022; Muslimin et al., 2017). Nevertheless, challenges such as low-quality cocoa due to pest and disease infestations and limited processing technology hinder the industry's progress (Cilas & Bastide, 2020). A more innovative approach in estate development that emphasizes productivity, efficiency, and competitiveness is thus essential (Aneani et al., 2017). Despite its potential, Indonesia's cocoa export performance still lags behind other producing countries, indicating lower comparative competitiveness (Fahmid et al., 2022). To overcome this, strategies such as replanting, improving fermentation techniques, enhancing seed quality, using pest-resistant varieties, and expanding downstream industries must be adopted to boost product quality, increase added value, and improve farmers' incomes (Feby et al., 2021; Zulfiandri, 2023).

A thermochemical process called pyrolysis uses high temperatures and no oxygen to break down organic materials. Cocoa bean and pod shells can be converted into more valuable products in the cocoa industry by the process of pyrolysis. Bioenergy in the form of bio-oil and bio-gas can be produced by pyrolyzing cocoa shells. Because of its high calorific value, the resulting bio-oil has the potential to replace fossil fuels (Akinola et al., 2018; Mumbach et al., 2022). Moreover, pyrolysis can also produce biochar which can be used as an alternative fuel or fertiliser (Tsai et al., 2018). Moreover, pyrolysis can also produce liquid smoke that can be used in the food and cosmetic industries (Handojo et al., 2020; Wijaya et al., 2019). Although pyrolysis offers many benefits, there are some challenges that need to be overcome. One of them is the optimisation of pyrolysis conditions to maximise the yield of the desired product. Research shows that the right temperature and heating rate are crucial to improve the quality of pyrolysis products. The study by Handojo et al. (2020) has proven that cocoa bean shells can be utilized through a pyrolysis process into liquid smoke containing bioactive compounds with various benefits. This finding opens a great opportunity to develop a cocoa agro-industry model based on pyrolysis technology as a strategy for product diversification and increasing added value. However, until now there has not been much research to develop an integrated agro-industrial approach with pyrolysis technology on an applicable scale, especially with the orientation of sustainable cocoa derivative product development (Handojo et al., 2020).

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This study aims to analyse the utilisation of cocoa shells through fermentation and pyrolysis processes into three main derivative products, namely liquid smoke, charcoal (biochar), and bio-oil. This study presents an innovative approach to cocoa shell waste-based agro-industrial development through the integration of fermentation and pyrolysis processes to produce three economically valuable products: liquid smoke, biochar and bio-oil. This approach differs from previous studies that only focused on one processing method or one type of product. For example, the study by Villasanaet al. (2023) only explored the value enhancement of cocoa shells through thermochemical pyrolysis and catalytic upgrading to produce volatile compounds, without the involvement of fermentation or integrated multi-product production (Villasana et al., 2023). Meanwhile, the study by Wijaya et al. (2019) did produce liquid smoke and charcoal from cocoa waste, but the approach used is general and does not prioritize agro-industry development systematically and has not touched on detailed product analysis such as charcoal porosity (Wijaya et al., 2019).

In addition, this study also examined the pore structure of cocoa shell pyrolyzed charcoal as part of the product quality evaluation. This focus has not been found in many similar studies, where generally biochar from other biomass such as apricot or heavy oil is studied in terms of quality improvement through co-pyrolysis without specific exploration of functional materials (Zhuang et al., 2022). This integrated approach provides significant added value not only in the aspect of biomass waste utilization technology, but also in the context of local economic sustainability based on agricultural products such as cocoa. Thus, this article makes a novel contribution to the development of a sustainable cocoa agro-industry through integrated technology engineering.

2. Methods

Cocoa shells were collected from cocoa pods in Central Mamuju Regency, West Sulawesi Province. The cocoa beans were then fermented by adding media and the skins were dried until the moisture content reached 10-20% (w/b) according to Indonesian national standards. Prior to the pyrolysis process, cocoa pods are fermented to reduce moisture content, improve homogeneity, and reduce the content of interfering compounds such as complex lignin (Chen et al., 2019; S. Wang et al., 2017). Fermentation can also improve pyrolysis efficiency by opening up the structure of cellulose and hemicellulose. After fermentation, the cocoa pods are dried and put into the pyrolysis reactor with the combustion temperatures used are 112, 212, 312, 412, and 512°C with a combustion time of 5 hours (Handojo et al., 2020; Kouadio et al., 2019). During this process, the cocoa shells will decompose into three main phases, namely 1) the solid phase produces biochar (charcoal) in the form of solid carbon residue which is rich in pores and has potential as an adsorbent, fertiliser, or active ingredient. 2) The liquid phase produces bio-oil, a complex mixture of organic compounds that can be used as fuel or a source of bioactive chemical compounds. 3) The gas phase, where some of the pyrolysis gas is condensed into liquid smoke, contains phenolic, carbonyl, and acidic compounds that are antimicrobial and used as natural preservatives or disinfectants (Anca-Couce, 2016; Moldoveanu, 2019).

Important aspects in this process are temperature regulation, residence time, and gas condensation system. The gas formed during pyrolysis will be directed to the cooling system to produce liquid smoke through the condensation process, while the solid residue in the reactor becomes biochar, and the other non-condensate liquid fraction is collected as bio-oil (Song et al., 2019; Q. Wang et al., 2020; Zong et al., 2020). The cocoa shell charcoal from the pyrolysis process was then analysed by SEM to see the morphological structure, and then the liquid smoke product was analysed using Fourier Transform Infrared (FTIR) analysis to characterise the chemical compounds. The analytical method was chosen because each molecule has a unique spectral ‘fingerprint’, allowing identification of organic and inorganic compounds with high accuracy. In addition, it is very useful to determine the functional groups in the molecule, such as hydroxyl, carbonyl, or amine. This information is important in understanding the chemical structure of compounds and their reactivity (Du et al., 2014; Mumbach et al., 2022). Through this approach, previously unutilised cocoa shell waste can be transformed into three products that not only have high economic value, but are also environmentally friendly, thus supporting the principles of circular bioeconomy and sustainable agro-industrial development.

3. Results and Discussion

Pyrolysis Process

Cocoa shells collected from Central Mamuju Regency, West Sulawesi Province, went through a series of stages involving fermentation and drying. Fermentation is carried out to reduce the moisture content of the cocoa shells, which are then dried to a moisture content of 10-20% (w/b), in accordance with Indonesian national standards. The purpose of fermentation is to improve the homogeneity of the cocoa shells and reduce the content of interfering compounds such as complex lignin. The fermentation process is also effective in opening up the structure of cellulose and hemicellulose, thus increasing the efficiency of subsequent pyrolysis. After the fermentation and drying process, the cocoa pods were put into the pyrolysis reactor with various combustion temperatures, namely 112°C, 212°C, 312°C, 412°C, and 512°C, with a combustion time of 5 hours. The results of pyrolysis of cocoa pod shells with a moisture content of 9.83%, while cocoa pods of Central Mamuju Regency with lignin content for cocoa pod shells 50.34%, alpha cellulose 28.82 and hemicellulose 1.25%. Lignin content depends on different types of raw materials and burner temperature conditions. Lignin does not have repeat units like hemicellulose and cellulose, but consists of complex phenolate units. Lignin is an amorphous copolymer complex consisting of guaiacyl (G), p-hydroxyphenyl (H), and syringyl (S) units that interconnect as éter bonds and carbon-carbon linkages (D. Shen et al., 2015). During the pyrolysis process, the cocoa shells decompose into three main phases:

1. Solid Phase: This phase produces biochar or charcoal that is rich in pores. This biochar has potential as an adsorbent, fertiliser, or active ingredient for various industrial applications. The biochar results show success in increasing sorption capacity, which can be utilised in water or air treatment.
2. Liquid Phase: The liquid phase produces bio-oil, which is a complex mixture of organic compounds. These bio-oils have potential as alternative fuels or sources of bioactive chemical compounds that can be used in various chemical and energy industries (Mohanty et al., 2024).
3. Gas Phase: The gas formed during pyrolysis is condensed into liquid smoke, which contains phenolic, carbonyl, and acidic compounds. These compounds have antimicrobial properties and can be used as natural preservatives or disinfectants, further adding to the economic value of the resulting product. Due to the potential advantages of these substances, cocoa liquid smoke has significant commercial value. Cocoa liquid smoke is also known to have strong antioxidant properties. According to research, liquid smoke made from cocoa shells having a moisture content between 10% and 25% showed strong antioxidant activity. Cocoa liquid smoke has the potential to be used as a natural food preservative due to its antioxidant properties (Budaraga et al., 2019).

Setting the combustion temperature is a key aspect in the pyrolysis process. The higher the temperature used, the greater the amount of biochar produced, but with a decrease in bio-oil and gas content. In addition, the combustion time set for 5 hours has provided optimal results in producing the desired product fraction. The gas condensation process is also very important, where the pyrolysis gas formed is directed to the cooling system to produce liquid smoke rich in chemical compounds with antimicrobial activity. This stage was conducted to determine the effect of temperature variation on the weight and yield (%) of liquid smoke produced from the dry distillation process of cocoa pod skin. The experimental results show that temperature plays an important role in determining the amount of liquid smoke product produced.

Table 1. Yield of Cocoa Pod Liquid Smoke

Temperature (°C)	Cocoa Liquid Smoke	
	Weight (g)	Yield (%)
112	28	3.17
212	177	20.05
312	98.5	11.15
412	96	10.87
512	36	4.07

To calculate the yield (%) of the experiment as in the table above, the formula commonly used in biomass distillation or pyrolysis processes is:

$$Yield\ (\%) = \left(\frac{Weight\ of\ yield\ (gram)}{Weight\ of\ starting\ material\ (gram)}\right) \times 100\%$$

Steps to Calculate Yield (%) is by weighing the initial weight of raw materials in the form of dried cocoa peels as much as 883 grams. Then pyrolysis/destillation is carried out at a certain temperature. Then collect the condensation results in the form of liquid smoke and weigh the weight using the formula above to calculate the yield. The results of dry distillation of cocoa pod samples showed that increasing the temperature had a significant effect on the weight and yield of liquid smoke produced. The results showed that dry distillation temperature has a significant effect on the weight and percentage yield of liquid smoke produced from cocoa pods. At 112°C, the yield produced was 3.17% (28 g), while at 212°C there was a drastic increase to reach 20.05% (177 g). This shows that 212°C is the optimum point in the dry distillation process to produce liquid smoke from these raw materials. After the temperature increased past the optimum point, the yield decreased gradually. At 312°C and 412°C, the yield dropped to 11.15% and 10.87%, respectively. Another significant decrease occurred at 512°C, where the yield was only 4.07% (36 g). This decrease in yield is most likely due to the thermal degradation of volatile compounds and the formation of products that do not re-condense into liquid smoke. In general, the trend of the data forms a downward open parabolic curve, which can be represented by a quadratic regression model. Quadratic regression provides a good predictive approach to determine the ideal temperature in cocoa biomass-based liquid smoke production. This model shows that there is a non-linear relationship between temperature and yield, where there is a maximum point at a certain temperature.

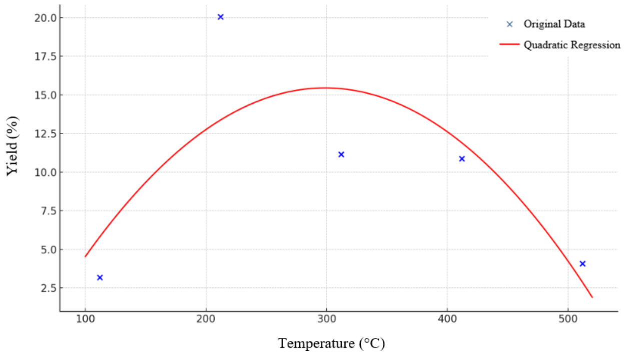

Figure 2. Quadratic regression model

The quadratic regression model obtained is:
$Y = -0.00027671T2+0.16529T-9.2376$

where:
Y = yield (%)
T = temperature (°C)

The analysis showed that the relationship between heating temperature and yield (%) of liquid smoke followed a quadratic non-linear pattern. The yield of liquid smoke increased significantly until it peaked at 212°C (20.05%), then decreased at higher temperatures. This can be explained from a thermal point of view. At low temperatures (112°C) very little product is produced, the decomposition of organic matter is not optimal, resulting in only 3.17% yield of liquid smoke. The temperature is not enough to break down complex compounds such as lignin, cellulose, and hemicellulose efficiently (Kawamoto, 2007). At 212°C, there is maximum decomposition of volatile and semi-volatile compounds, especially lignin and cellulose, which are the main components of cocoa biomass. At this temperature, the thermal decomposition of lignocellulose reaches its peak, producing the maximum amount of liquid smoke conductivity (Bridgwater, 2012). This explains the highest yield values. After 212°C, further degradation or even carbonisation occurs, so the volatile compounds turn into gas or solids (charcoal) instead of liquid smoke. The yield drops dramatically, to only 4.07% at 512°C. This can be explained scientifically that at high temperatures, the volatile compounds previously formed undergo further degradation into gases such as carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4), which cannot be condensed into liquid form. In addition, at high temperatures, phenolic compounds tend to polymerise to form tar, or even decompose completely so that they no longer contribute to the formation of liquid smoke.

The dominant carbonisation process at high temperatures also causes most of the organic components to turn into solid residues in the form of char. Therefore, the higher the distillation temperature, the lower the liquid fraction that can be obtained, as most of the product turns into the gas or solid phase. This is in line with previous research which states that excessive heating in the pyrolysis or dry distillation process can cause loss of volatile compounds due to thermal decomposition (Liu et al., 2022; Oginni & Singh, 2020; Rathika et al., 2024). Thus, a temperature of 212°C can be considered as the optimum temperature in the dry distillation process of cocoa pods to obtain the highest yield of liquid smoke. Temperatures above this value tend to be inefficient in liquid smoke production and produce more gas and solid residue. Increasing pyrolysis temperature tends to reduce biochar yield but increase carbon content (Zhang et al., 2020). This finding is in line with previous literature on pyrolysis of lignocellulosic biomass, where the middle temperature (200-250°C) is the optimal range for liquid smoke production with good quality and quantity (Bridgwater, 2012; Mohan et al., 2006).

FTIR Analysis

The next stage is analysis using Fourier Transform Infrared (FTIR). This analysis technique is used to identify functional groups in a material, which is very useful in the pyrolysis process. FTIR analysis can provide deep insight into the chemical and structural changes of the material that occur during the process. With FTIR, researchers can ensure that pyrolysis products have the desired properties for specific applications, such as in the manufacture of activated carbon for supercapacitors or catalysts for liquid fuel production. FTIR analysis results for cocoa pods of Mamuju Tengah Regency can be seen in Figure 1.

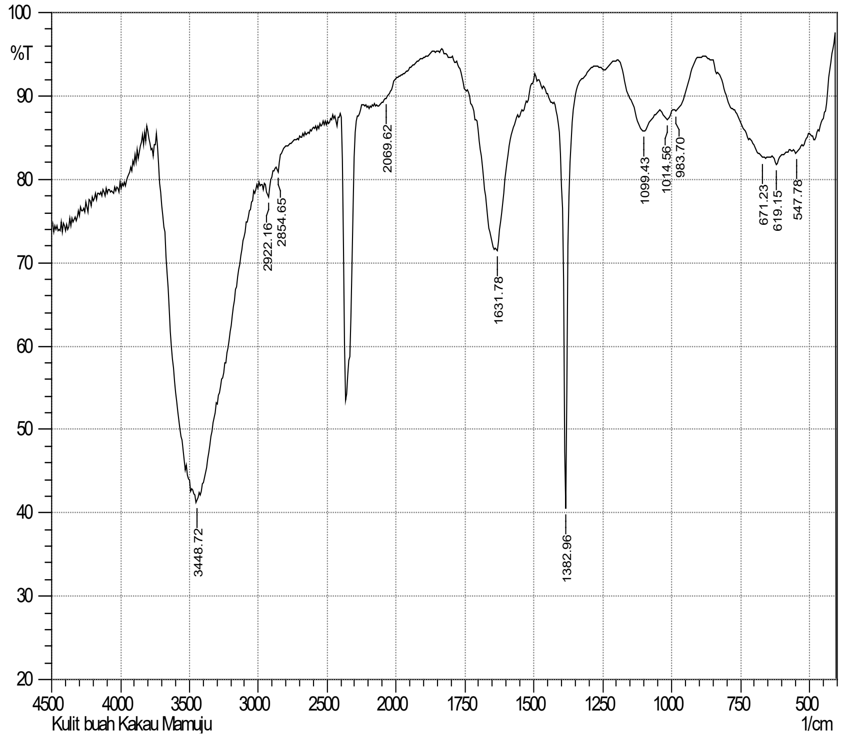

Figure 2. FTIR analysis for cocoa pod skin of Mamuju Tengah district

Based on the FTIR spectrum in Figure 1, significant peaks can be interpreted in the spectrum of cocoa pod skin (with absorbance numbers in cm-^{1}):

Table 2. Interpretation of FTIR Analysis of Cocoa Pod Peels

Wavelength (cm^{-1})	Interpretation
3448.72	Indicates the presence of hydroxyl (-OH) groups, usually associated with hydrogen bonded alcohol, phenol, or water compounds.
2924.65	This peak is generally attributed to the C-H stretch of aliphatic groups (CH_2 and CH_3), which are often found in lipid or fat compounds.
2089.62	These peaks can come from triple bond groups such as C≡C (alkyne) or C≡N (nitrile), although they tend to be smaller in intensity than other groups.
1631.78	Indicates C=O (carbonyl) stretch vibrations, which are often found in compounds such as carboxylic acids, esters, or amides.
1382.98	This peak can be attributed to C-H symmetrical stretching of the methyl group (CH_3) or deformation vibrations.
1009.43–1041.49	This range generally indicates C-O vibrations of alcohols, esters, or sugars. This is consistent with the presence of polysaccharides or lignocellulose-derived compounds.
671.23–647.78	Indicates aromatic C-H out-of-plane bending vibrations, which often occur in aromatic compounds such as lignin.

The spectrum in Figure 1 shows the presence of major organic compounds such as water (hydroxyl groups), lipids or fats (C-H aliphatic), polysaccharides (C-O), aromatic compounds or lignin (C-H aromatic). These FTIR spectra indicate that the cocoa pods have lignocellulose components, lipids, and possibly phenolic compounds that are relevant to their applications, such as for bioactive materials or biomaterials. These compounds could be used in various industrial applications, including cosmetics and food (Londoño-Larrea et al., 2022).

The next step is to conduct FTIR analysis for cocoa pod shell charcoal. Fourier Transform Infrared (FTIR) spectroscopy is an analytical technique used to identify and characterise chemical components in various materials, including charcoal. This technique utilises the infrared spectrum to detect various functional groups in the sample, which can provide important information about the chemical structure and physical properties of the charcoal. The results of FTIR analysis for cocoa pod shell charcoal can be seen in Figure 2.

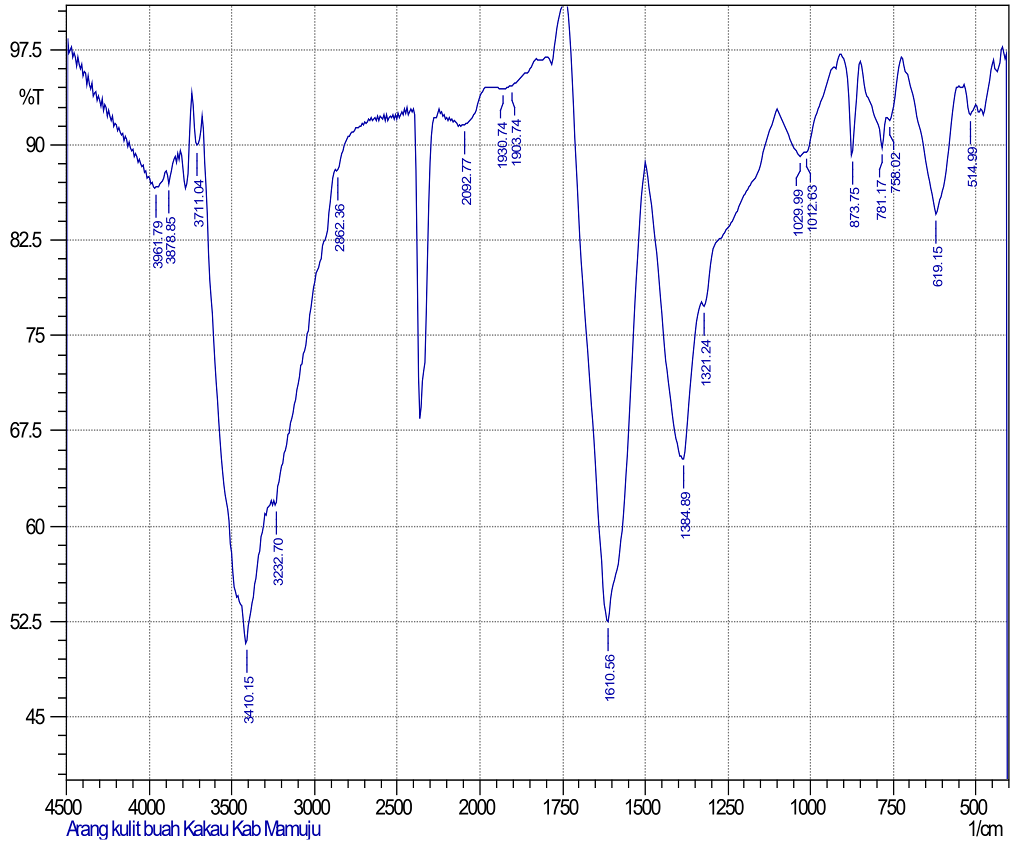

Figure 3. FT IR analysis for cocoa pod shell charcoal of Mamuju Tengah Regency

Based on the FTIR spectrum in Figure 2, the main peaks can be analysed. The analysis results can be seen in Table 3:

Table 3. Interpretation of FTIR Analysis of Cocoa Pod Peels

Wavelength (cm^{-1})	Interpretation
3870.78–3711.04	This broad peak indicates the presence of hydroxyl (-OH) groups, which are often indicated in alcohol or water compounds, although the intensity may decrease due to the carbonisation process.
3401.05	More pronounced -OH stretching vibrations, indicating adsorbed water or remaining phenolic groups. The hydroxyl group at 3401.05 cm^{-1} indicates that cocoa shell charcoal has the ability to adsorb water or polar compounds. This can be utilised for adsorption applications in water filtration or removal of organic pollutants such as dyes or heavy metals.
2922.70	Indicates aliphatic C-H stretch vibrations (CH_2 or CH_3), which tend to decrease in carbonised materials.
2022.77	This peak may indicate the presence of triple bonds (C≡C or C≡N) in small amounts.
1631.74	C=O (carbonyl) stretch vibrations or C=C asymmetric vibrations in aromatic compounds. These are common in carbon materials containing conjugated aromatic structures.
1384.90	This peak is related to the C-H deformation vibrations of the methyl group (CH_3) or aromatic structure.
1212.41	Indicates C-O vibrations of esters, phenols, or other compounds with oxygen groups.
1029.59	A more dominant C-O stretch vibration, indicating the possible presence of ether or alcohol groups.
871.75; 781.17; and 619.16	An aromatic C-H out-of-plane bending vibration, which confirms the presence of an aromatic structure or conjugated carbon compound.

The FTIR spectrum of the cocoa pod shell charcoal shows the presence of hydroxyl (-OH) and carbonyl (C=O) groups, although their intensity decreases due to carbonization (Omole et al., 2024). Aromatic structures are dominant, which is typical for charcoal with a high carbon content. Other oxygen compounds such as phenols or ethers are less likely (León et al., 2022; Wijaya et al., 2024). The carbonisation process appears to have removed most of the aliphatic groups, but left aromatic structures and conjugated carbon compounds, which are typical for activated carbon materials. The hydroxyl group at 3401.05 cm^{-1} indicates that cocoa shell charcoal has the ability to adsorb water or polar compounds. This can be utilised for adsorption applications in water filtration or removal of organic pollutants such as dyes or heavy metals. Vibrations at 1631.74 cm^{-1} (aromatic C=C) and peaks in the range 871.75-619.16 cm^{-1} indicate the presence of conjugated aromatic carbon structures. This structure is commonly found in activated carbon and provides good chemical properties, such as high adsorption capacity useful for adsorbing organic molecules, toxic gases, or vapours as well as thermal and chemical stability to make this charcoal suitable for applications at high temperatures or extreme environments. Vibrations at 1212.41 cm^{-1} (C-O) and 1631.74 cm^{-1} (C=O) indicate oxygenated functional groups, which are important for enhancing the hydrophilic properties and polarity of the charcoal (Jiang et al., 2023; C. Wang et al., 2021). This supports its application in the adsorption of certain chemicals, such as acid gases (H_2S, CO_2), and organic and inorganic pollutants in aqueous solutions (J. Shen et al., 2018; Tofighy & Mohammadi, 2022). The reduced intensity of the peak at 2922.70 cm^{-1} (C-H aliphatic) indicates the degradation of non-aromatic organic matter during carbonisation. This indicates the formation of a graphitic carbon structure, which improves electrical conductivity.

SEM Analysis

To analyse the morphology of the biochar produced from the solid phase, Scanning Electron Microscopy (SEM) analysis was conducted. By heating organic materials without oxygen, a thermochemical process known as pyrolysis converts them into charcoal. In this study, pyrolysis was used to make charcoal using cocoa pod shells (CPH) as raw material. Scanning electron microscope (SEM) analysis was required to understand the morphological structure of the resulting charcoal. Figure 4, 5 and 6 displays the findings from the SEM investigation.

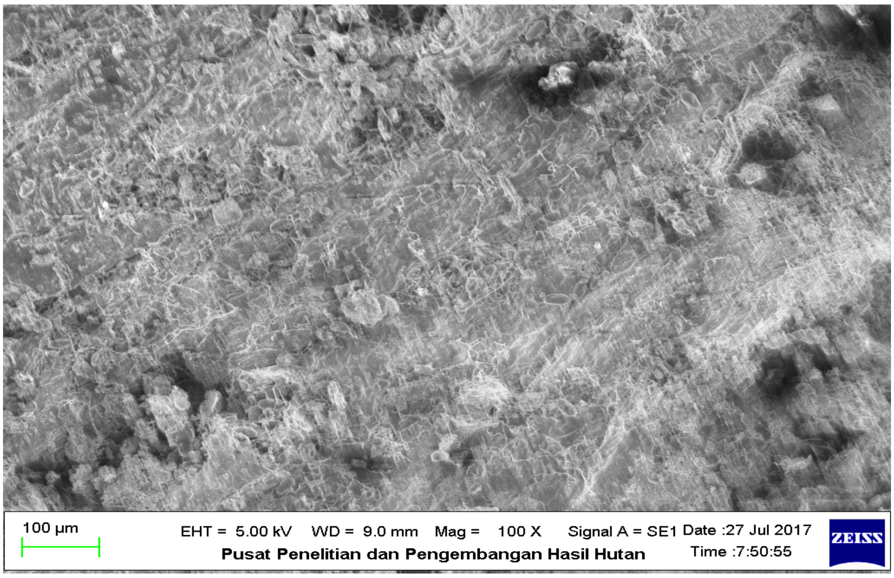

Figure 4. SEM analysis results for cocoa pod shell with 100x Magnification, 100 µm scale

Figure 4 shows a rough and irregular surface with visible structures resembling fibers and clusters of material. The surface texture indicates a relatively porous nature with some clear channel-like structures, which is typical for adsorbent materials. This structure is beneficial for applications in adsorption, such as water filtration or pollutant removal, due to the availability of voids for trapping particles. This morphology shows that the charcoal has an ample surface area, which is desirable for its adsorptive capacity, as more surface area allows for more contaminants to be adsorbed.

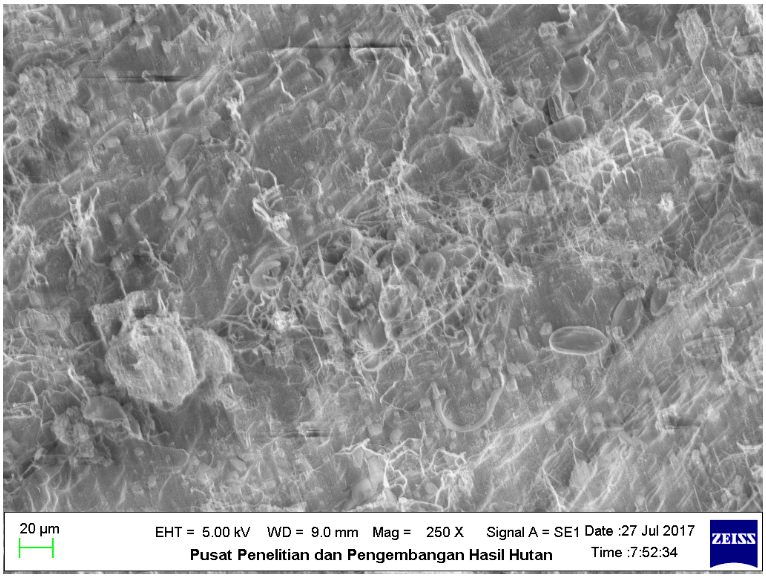

Figure 5. SEM analysis results for cocoa pod shell with 250x Magnification, 100 µm scale

Figure 5 shows a combination of smooth and rough areas, with structures resembling fibers and rounded aggregates. This suggests that the material has a hybrid structure, which could be beneficial for both adsorption and catalytic reactions. The larger structures in the image could enhance bulk adsorption properties, while the finer ones might be better at absorbing specific smaller molecules. The varied surface features suggest that the charcoal could be versatile in terms of the types of contaminants it can adsorb, ranging from larger organic compounds to smaller, more chemically active species.

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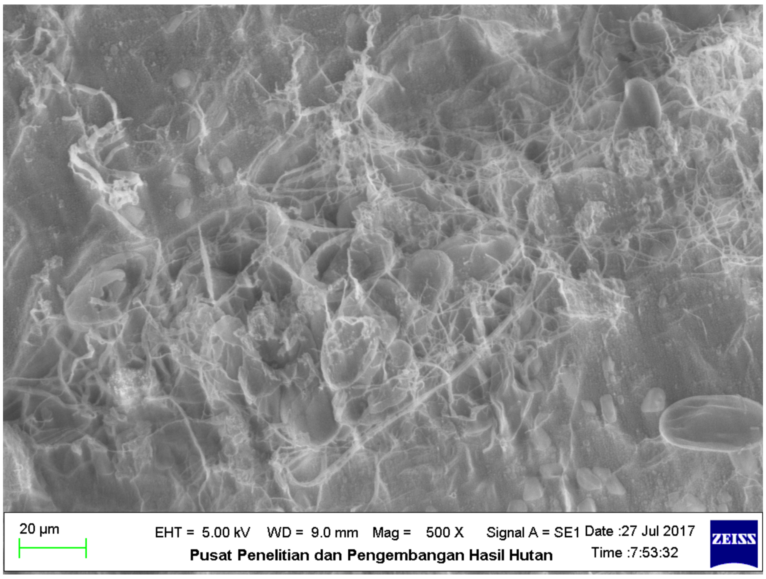

Figure 6. SEM analysis results for cocoa pod shell with 500x Magnification, 100 µm scale

At a higher magnification, the fine structure of the charcoal becomes more apparent. You can see more intricate network patterns and fibrous-like formations. The porosity is more pronounced here, with visible interconnecting pores that provide additional surface area for adsorption. These fine pores are especially suitable for micro and mesopore adsorption, such as absorbing organic molecules or small inorganic pollutants. The detailed structure observed at this level indicates that the charcoal can interact effectively with a variety of molecules, including organic contaminants and heavy metals, due to its high porosity.

SEM analyses of the cocoa pod charcoal shown in Figures 4, 5 and 6 provide valuable insights into its morphological structure and potential applications. SEM analysis reveals the small pore structure of the cocoa pod charcoal. This indicates that the charcoal has a highly porous surface, which is important for its sorption ability. Such small pores are particularly suitable for trapping and adsorbing inorganic and organic contaminants, which is beneficial for filtration applications. Additionally, high porosity is a key feature of charcoal, indicating that it has a large surface area available for absorption. This characteristic is particularly valuable in industries that require efficient filtration, such as water treatment and pollution control. The micro and mesoporous structure of charcoal, makes it effective in adsorbing organic and inorganic contaminants. This includes the removal of heavy metals such as Pb and Cd, as well as pollutants such as nitrates and phosphates. Additionally, charcoal can serve as an activated carbon medium to remove odour, colour, and organic contaminants from wastewater (Dolatkhah et al., 2022; Labied et al., 2022; Mopoung et al., 2014; Tuaprakone et al., 2011).

4. Conclusion

The cocoa shell pyrolysis process with prior fermentation and drying can produce three main products: biochar, bio-oil, and liquid smoke. This process not only increases the efficiency of using cocoa shell waste, but also produces products that can be applied in various industries, such as filtration, water treatment, alternative energy, and preservation.

212°C can be considered as the optimum temperature in the dry distillation process of cocoa pods to obtain the highest yield of liquid smoke. Temperatures above this value tend to be inefficient in liquid smoke production and produce more gas and solid residue. Increasing the pyrolysis temperature tends to decrease the biochar yield but increase the carbon content. SEM and FTIR analyses provide a clear picture of the potential and value of the resulting products, which is in line with the principles of sustainable agro-industrial development and circular bioeconomy.

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