







# Converting arabica coffee parchment into value-added products: technical and economic assessment

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## ABSTRACT:

The coffee processing industry is experiencing a continuous rise in residues due to increased coffee-cherry production. However, the utilization of coffee parchment, which contains toxic compounds, remains limited and requires further investigation. This study aims to convert coffee parchment into biochar for potential use as a raw material for porous carbon material. The research was conducted using a purpose-built pilot-scale reactor. The goal was to address challenges related to operational cost, simplicity in operation, and maintenance, utilizing the Net Present Value (NPV) approach. Results indicated that coffee parchment comprised 34.5% biochar, 42.15% bio-oil, and balanced un-condensable-gas. Additionally, biochar products consisted of 42.02% fixed carbon and 38.63% volatile matter. The pyrolysis equipment designed for coffee parchment showcased economic viability, considering optimized annual operating days and scalability for production.

**Key words:** Biochar; Economic analysis; Hydrogen storage; Pyrolysis.

## 1 INTRODUCTION

The adoption of renewable energy is not merely a choice but a requirement, given the declining fossil fuel production and its detrimental environmental effects. This shift has resulted in a heightened need for sustainable and clean energy sources. (Dyjakon; Noszczyk; Mostek, 2021; Fan et al., 2017; Mishra; Mohanty, 2018; Sarkar; Wang, 2020; Sekar et al., 2021; Setter et al., 2020a). Some green technologies such as solar power, wind power (Kansongue; Njuguna; Vertigans, 2022) and biomass are significant contributors to harnessing renewable energy (Raihan et al., 2020; Setiawan et al., 2022). These energy sources have the potential to ensure safety and stability in supply. As a result, extensive research, both experimental and numerical, has been focused on optimizing energy utilization (Aslani et al., 2013; Lilas et al., 2022).

As a nation dependent on agriculture, Indonesia possesses abundant potential resources, including geothermal, hydro power, solar power, and biomass. Furthermore, the government aims to decrease greenhouse emissions by 29% by 2030 (Maj, 2018; Risky; Yusuf; Setiawan, 2020). Extensive exploration of all renewable energy sources, with a particular focus on biomass, is underway to meet this goal.

Currently, biomass stands as the most extensively utilized renewable energy source due to its abundance, cost-effectiveness, and significant interest from investors (Kaczor; Buliński; Werle, 2020; Kung; Zhang, 2015; Li et al., 2015). Moreover, the conversion of biomass into fuel has attracted substantial investment. Simultaneously, its utilization has addressed the challenge of managing agricultural residues, often seen as waste (Biswas et

al., 2017). In Indonesia, there is a considerable accumulation of waste from both plantations and coffee production. Initial studies have affirmed the potential of coffee plantation waste as a viable fuel source (Alchalil et al., 2021; Chala et al., 2018; Kiggundu; Sittamukyoto, 2019; Setter et al., 2020). Additionally, between 2020 and 2021, Indonesia witnessed a coffee production of 10.3 million bags or 618,000 tons (Lim; Zwicker; Wang, 2019), with nearly 50% of the waste originating from the process of fruit conversion into coffee beans (Chala et al., 2018).

Thermal conversion of biomass is a viable approach to minimize coffee production waste and involves diverse processes like combustion, torrefaction, hydrothermal carbonization, gasification, and pyrolysis (Christoforou; Fokaidis, 2019; Varma et al., 2018). Pyrolysis has gained popularity due to its emission-free process, resulting in biochar, bio-oil, and syngas as products. The operating temperature in pyrolysis is notably lower compared to gasification (Varma et al., 2018). While pyrolysis operates at a higher temperature range of 350-650°C, in contrast to torrefaction (220-300°C), the resulting biochar, bio-oil, and pyro-gas products exhibit superior quality (Christoforou; Fokaidis, 2019). Pyrolysis is a thermochemical breakdown of biomass, involving heating at temperatures ranging from 350-650°C in an oxygen-deprived environment. The outcome of this process encompasses three primary components: biochar, a bio-oil derived from volatile materials that can be condensed into a liquid phase, and non-condensable gases (CO, CO<sub>2</sub>, CH<sub>4</sub>, and H<sub>2</sub>) (Manyà; Azuara; Manso, 2018). Subsequently, previous studies carried out on various biomass types are shown in Table 1. However, despite its numerous advantages, the broader application of pyrolysis

technology is hindered by inefficient reactor design and high energy consumption during the process (K N et al., 2022). Exploration of coffee parchment pyrolysis remains relatively limited, and further research is essential, particularly concerning biochar and bio-oil products (Kiggundu; Sittamukyoto, 2019).

Hydrogen is considered a promising energy source for widespread utilization in the future. The crucial aspect lies in storing this energy efficiently in materials with high volumetric and gravimetric density (Ramesh; Rajalakshmi; Dhathathreyan, 2015). Carbon-based materials exhibit a notable hydrogen storage capacity owing to their porous microstructure and high specific surface area, surpassing that of graphite and single-walled carbon nanotubes. Multiple studies have demonstrated the potential of activated carbon derived from biomass as a viable storage material (Chen et al., 2012; Schaefer et al., 2016; Zhao et al., 2017). However, to the best of our knowledge, investigating carbon material for hydrogen storage derived from coffee parchment remains unexplored. Therefore, conducting a targeted investigation to address the characteristics of carbon material derived from coffee parchment is essential.

The primary aim of this study was to analyze the pyrolysis procedure and the properties of resulting products when utilizing coffee parchment as a raw material for hydrogen storage. Additionally, the focus was on evaluating the efficiency of a custom-built pyrolysis reactor specifically designed for coffee parchment. The reactor, with a 30-liter capacity, was structured to mimic real-life industry conditions closely. The research also sought to address challenges related to achieving cost-effectiveness, simplifying operations, and ensuring easy maintenance. A comprehensive assessment of the viability of this pyrolysis technology was conducted utilizing the Net Present Value (NPV) approach.

## 2 MATERIAL AND METHODS

### 2.1 Materials

Biomass of Gayo Arabica coffee parchments was collected from Bener Meriah Regency, Aceh, Indonesia. The ‘parchment’ here refers to the thin skin of the coffee bean, separated using a dehulling machine. In each operation, 2.00 kg of coffee parchments were sun-dried for 2 to 3 days and subsequently loaded into the pyrolysis chamber.

### 2.2 Experimental Set-Up

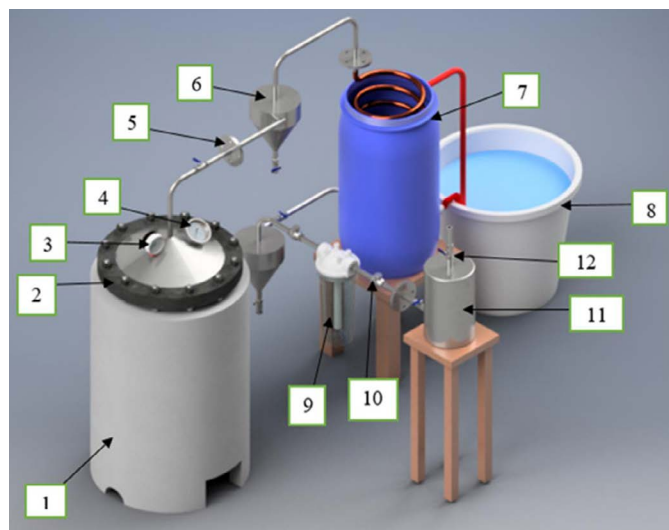
The pyrolysis chamber was engineered to accommodate a maximum of 4.0 kg of raw materials, maintaining temperature and pressure conditions at 600°C and 5 bar (g), respectively. The experimental arrangement is depicted in Figure 1, comprising five primary components: furnace, reactor, separator, condenser, and gas storage tank. The specific dimensions of each part can be found in Table 2.

With a design pressure of 5 bar, the reactor was initially calculated to have a minimum thickness of 0.52 mm using stainless-steel material, although a 4 mm thickness was utilized in the actual design. To aid biochar collection, a stainless-steel wire mesh bucket was incorporated within the reactor. The reactor was seamlessly integrated into a furnace with dimensions of 235 mm inner diameter and 700 mm height. Additionally, a stainless steel separator with an outer diameter and thickness of 150 mm and 3 mm, respectively, was devised to segregate the liquid product from the reactor’s outlet stream. Within the condenser unit, a ½-diameter copper tube, spanning a total length of 600 cm, was employed. This copper tube coil was placed within a 32 L polymer drum filled with cooling

**Table 1:** Pyrolysis of various types of biomass.

| Feedstock         | Temperature condition (°C) | Product Yield |             | Ref.                           |
|-------------------|----------------------------|---------------|-------------|--------------------------------|
|                   |                            | % Bio-char    | % Bio-oil   |                                |
| Coffee parchment  | 350-550                    | 29.9-35.09    | -           | (Kiggundu; Sittamukyoto, 2019) |
|                   | 350-450                    | 34.68-39.62   | 27.77-31.94 | (Setter et al., 2020)          |
| Rice husk         | 450                        | 24.0          | 47.3        | (Biswas et al., 2017)          |
| Rice straw        | 400                        | 33.5          | 28.4        | (Biswas et al., 2017)          |
| Wheat straw       | 400                        | 34.4          | 36.7        | (Biswas et al., 2017)          |
| Corn corb         | 450                        | 35.0          | 38.1        | (Biswas et al., 2017)          |
|                   | 575                        | 25.4          | 49.5        | (Rout et al., 2016)            |
| Coconut shell     | 400-800                    | 27.6-33.6     | 48.7-47.5   | (Sarkar; Wang, 2020)           |
| Sawdust           | 500                        | 15            | 60          | (Park et al., 2019)            |
| Palm kernel shell | 500                        | 37.17         | -           | (Lee et al., 2017)             |
| Anchusa azurea    | 450                        | 37.46         | 31.31       | (Aysu et al., 2016)            |
| Cashew nutshell   | 400                        | 20            | 40          | (Moreira et al., 2017)         |
| Sugarcane bagasse | 390-980                    | 27.33-37.64   | 38.11-50.89 | (Al Arni, 2018)                |

fluid. Furthermore, a gas collecting tank, boasting a diameter of 150 mm and height of 250 mm, was fabricated to gather the un-condensable gases temporarily before transferring them to the main storage tank. In terms of piping, stainless steel pipes with a 1/2-inch diameter were utilized throughout this setup.



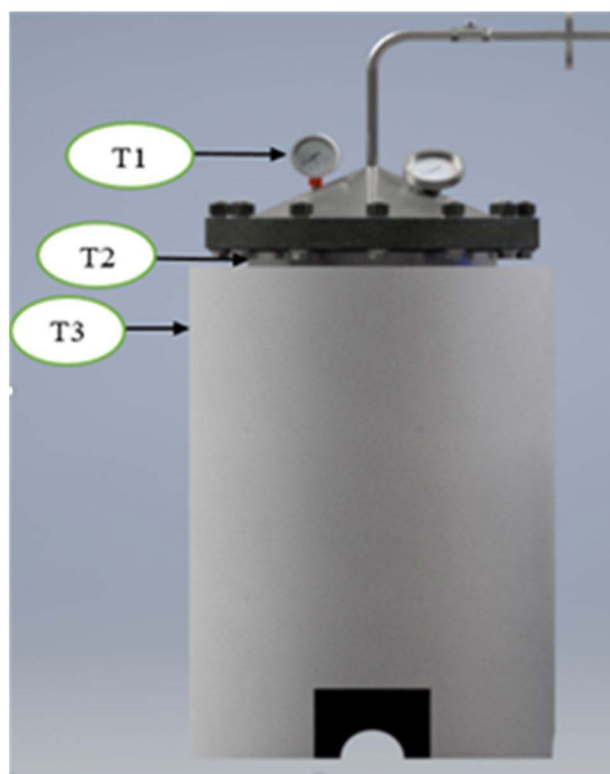
**Figure 1:** Pyrolysis experimental set up (1) furnace, (2) reactor, (3) pressure gauge, (4) thermometer, (5) flanges, (6) tar separator, (7) condenser, (8) water container, (9) moisture absorber, (10) check valve, (11) gas collecting tank, (12) syngas outlet valve.

**Table 2:** Pyrolysis apparatus geometry and sizes.

| Component           | Parameters                           | Size  |
|---------------------|--------------------------------------|-------|
| Reactor             | Tube diameter (mm)                   | 320   |
|                     | Tube height (mm)                     | 400   |
|                     | thickness (mm)                       | 4.0   |
|                     | Inner tube volume (cm <sup>3</sup> ) | 30300 |
|                     | Reactor weight (kg)                  | 15.2  |
|                     | Max. capacity (kg)                   | 4.0   |
| Furnace             | Furnace inside diameter (mm)         | 323   |
|                     | Furnace height (mm)                  | 700   |
|                     | ε Furnace effectiveness rating       | 0.8   |
|                     | Furnace power (W)                    | 9600  |
|                     | Furnace outer critical radius (mm)   | 470   |
| Separator           | LPG consumption per run (kg)         | 1.82  |
|                     | Deposition speed (m/s)               | 16.5  |
|                     | Separator diameter (mm)              | 150   |
| Condenser           | Copper tube diameter (in)            | 1/2   |
|                     | Copper tube length (cm)              | 600   |
|                     | Drum diameter (mm)                   | 320   |
| Gas collecting tank | Outer diameter (mm)                  | 150   |
|                     | Height (mm)                          | 250   |

## 2.3 Pyrolysis Experiments

2.00 kg of raw material was put into the reactor, and thorough checks on all connections was conducted to ensure a leak-free setup. Subsequently, water was introduced into the condenser drum, and the LPG stove was ignited. Before performing pyrolysis experiment, thermal decomposition of raw material was assessed under thermogravimetry analysis to find-out the temperature range for higher rate of thermal decomposition. The chosen temperature was set at 350°C. It took approximately 90 minutes to heat the reactor and achieve the desired 350°C temperature. Each run maintained a total retention time of 180 minutes, with no observed pressure build-up beyond this point. As shown in Figure 2, there are three measurement points of temperature, *i.e.*, T<sub>1</sub>, T<sub>2</sub>, and T<sub>3</sub>. During the process, the inside of the reactor was kept at a pressure of 3 bar (g).



**Figure 2:** Temperature measurement points.

## 2.4 Characterization

The attributes of Gayo Arabica coffee parchment were first assessed using thermogravimetric (TG) analysis, along with proximate and ultimate analyses. Based on TG analysis, the maximum temperature of thermal decomposition of raw materials was estimated. The outcomes of ultimate and proximate analyses (on an air dry-basis) were employed to establish the composition, encompassing sulfur, carbon, hydrogen, chlorine, nitrogen, oxygen, ash, volatile matter, and moisture.

### 3 RESULTS

The raw materials and the resulting pyrolysis products, specifically biochar and bio-oil, underwent proximate analysis using the standard procedures outlined in ASTM D 3302, ASTM D 3175, ASTM D 3174, and ASTM D 3172 to determine parameters such as moisture content, volatile matter, ash, and fixed carbon. The ultimate analysis standard for carbon, hydrogen, and nitrogen refers to ASTM D 5373, while sulphur and oxygen refer to ASTM D 4239 and ASTM D 5373.

The elemental and morphological analysis was conducted using a Scanning Electron Microscope-Energy Dispersive X-Ray (SEM-EDS) system provided by Thermo Fisher Scientific, specifically the Type E Prism equipped with Energy-Dispersive X-Ray Spectroscopy (EDS). Additionally, the assessment of latent heat value involved TGA and DSC analyses performed on a Mettler Toledo TGA/DSC machine featuring a high-temperature furnace. The analyses were conducted under nitrogen purging at flow and heat rates of 30 ml/min and 10°C/min, respectively. The samples were placed in an alumina crucible c.a. 10 mg and then heated from an ambient temperature to 1000°C.

The calorific value was assessed through a bomb calorimeter. Approximately 1 gram of the sample was placed in a crucible and introduced into a Koehler bomb calorimetric apparatus. Density and viscosity measurements were conducted using the Koehler K86200 Automatic Density Meter and Lauda Viscocool 6, respectively. Furthermore, heater power, power consumption, pump pressure and pump flow max of 2 kW, 2.10 kW, 0.55 bar, and 22 L/min were utilized. The functional groups present in both the coffee parchment raw material and the biochar product were examined using a Shimadzu Fourier Transform Infrared Spectrophotometer (FTIR)-8400S, operating within the range of 350-4000 cm<sup>-1</sup>. For chemical composition analysis, a GC-MS Shimadzu GCMS-QP 2010 Plus gas chromatography, equipped with an Rtx-5 MS capillary column (Crossbonds®, 5% diphenyl, 95% dimethyl polysiloxane, 30m, 0.25 mm id, 0.25µm), was utilized. Inert helium gas was employed during the experiments. The compounds were introduced into the mass spectrometer and passed through a high-performance quadrupole mass filter to generate high-quality mass spectra. The GCMS solution Ver. 2.6 software facilitated the transfer and smooth switching of the chromatograms.

For economic analysis, a cost model is formulated utilizing information from existing literature. The NPV approach is employed as the economic valuation technique in this study. Sensitivity analysis has been conducted for biochar and bio-oil sale prices, interest rates, annual operational days, and production scale.

## 3.1 Coffee Parchment Characteristics

### 3.1.1 Ultimate Analysis

Table 3 presents the outcomes of the ultimate analysis conducted on Gayo Arabica coffee parchment. The parameters analysed encompass overall sulphur, carbon, hydrogen, nitrogen, and oxygen, an contents. Notably, the carbon content is determined to be 44.0%, slightly below the 46.99% reported in preliminary research (Nurmalita et al., 2022). Interestingly, other studies reported that the carbon content produced under wet and dry conditions is 44.95% and 49.33%, respectively (Manrique et al., 2019). This suggests a potential variance in the carbon content of coffee parchments linked to different fruit varieties. The oxygen content in coffee parchments is notably high at 45.15%, deviating from the typical biomass range of 30 to 40% (Setiawan et al., 2019). This elevated value can be attributed to the ash content present in the coffee parchment.

**Table 3:** Ultimate analysis result of Gayo Arabica coffee parchment.

| Analysis Parameters | Unit (%) | Basis |
|---------------------|----------|-------|
| Total sulphur       | 0.28     | adb   |
| Carbon              | 44.00    | adb   |
| Hydrogen            | 6.19     | adb   |
| Nitrogen            | 1.04     | adb   |
| Oxygen              | 45.15    | adb   |

### 3.1.2 Proximate Analysis

The properties of Gayo Arabica Coffee parchment were evaluated under proximate analysis, as shown in Table 4. In this assessment, four parameters were determined including moisture, ash, volatile matter, and fixed carbon contents.

**Table 4:** Proximate analysis results of Gayo arabica coffee parchment.

| Analysis Parameters   | Unit (%) | Basis |
|-----------------------|----------|-------|
| Moisture in air-dried | 10.44    | adb   |
| Ash                   | 3.34     | adb   |
| Volatile matter       | 68.58    | adb   |
| Fixed carbon          | 17.64    | adb   |

From the results of the proximate analysis, it was determined that the coffee parchment had a moisture

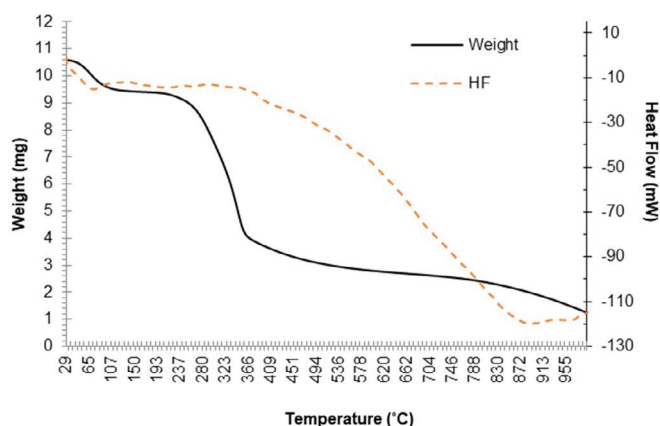


content of approximately 10.44%. High moisture content is detrimental to the calorific value of biomass fuel as it leads to energy loss and water vapor evaporation. The ash content was measured at 3.34%, which is considered optimal, as higher values tend to adversely affect calorific value and can result in slagging and fouling in the combustion chamber, impeding heat transfer. Additionally, the coffee parchment displayed a volatile matter content of approximately 68.58% and a fixed carbon content of about 17.64%. The high volatile matter and low fixed carbon content indicate the flammability of coffee parchments (Fernandez et al., 2021).

### 3.1.3 Thermal Analysis

The thermal characteristics of coffee parchment samples were analyzed using DSC/TGA with the Mettler Toledo TGA/DSC machine. The analysis involved heating the sample from room temperature up to 1000°C, as depicted in Figure 3.

Figure 3 presents the weight reduction of coffee parchment concerning temperature. This curve delineates three distinct stages: drying, devolatilization, and carbonation. The initial stage, drying or moisture loss, is characterized by a gradual decline in mass at lower temperatures. The drying process contributes to a 10% weight loss and transpires within the temperature range of 44 to 104°C. Subsequently, the devolatilization stage exhibits a sharp reduction in mass on the TG curve, accounting for a 50% weight loss and manifesting between 200 and 365°C. The final stage, carbonization, displays a gradual decline in mass. During this phase, there is a 30% reduction in weight, occurring at temperatures ranging from 857 to 988°C. Concurrently, the DSC curve indicates an endothermic reaction attributed to the inherent moisture in the coffee parchment below 109°C. Additionally, an exothermic reaction is predominantly observed, primarily due to material oxidation.

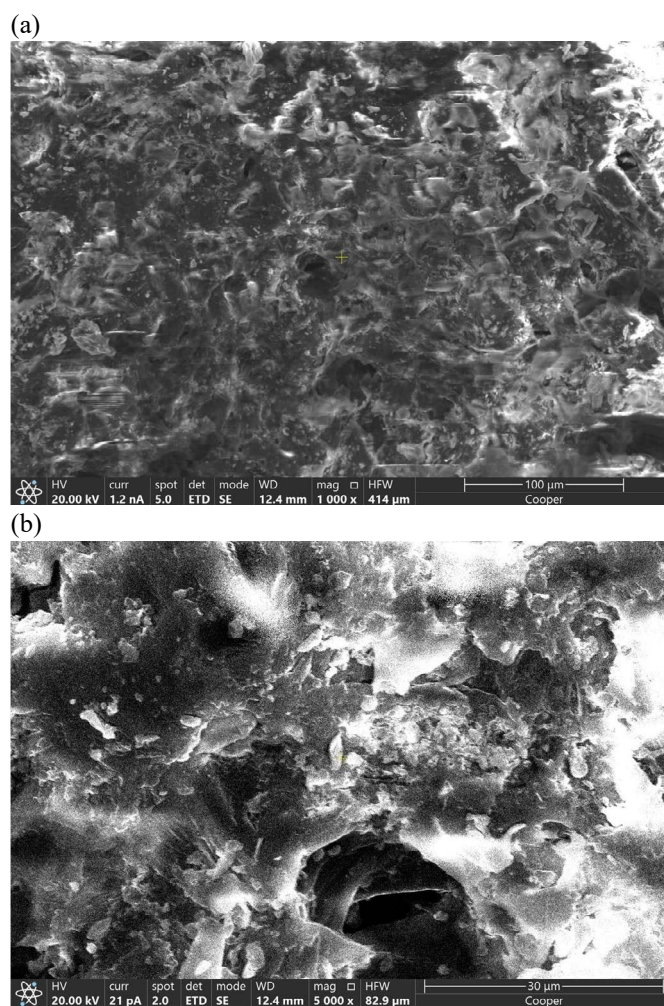


**Figure 3:** TGA and DSC curves of Gayo Arabica coffee parchment.

### 3.1.4 Morphological and Elemental Analysis

The surface structure and characteristics of Gayo Arabica coffee parchments were examined using SEM-EDS analysis to observe their morphology and topography prior to the pyrolysis process. Figure 4 illustrates SEM images of a sample magnified between 1000 to 5000 times, providing insight into the surface details. Elemental analysis of the coffee parchment surface is shown in Figure 5.

At a 1000x magnification, the surface of the SEM images displays an uneven and irregular texture without discernible micropores on the samples. However, when magnified to 5000x, the pores of the coffee parchment exhibit a coarse and irregular structure. Additionally, EDS analysis confirms a predominant presence of Carbon (C) at 72.2%, with Oxygen (O) exceeding 23.2 cps/eV. Trace amounts of elements such as Calcium (Ca), Phosphorus (P), Sulfur (S), Calcium (Ca), and Potassium (K) are also detectable.



**Figure 4:** SEM results of coffee parchments at (a) 1000x magnification and (b) 5000x magnification.

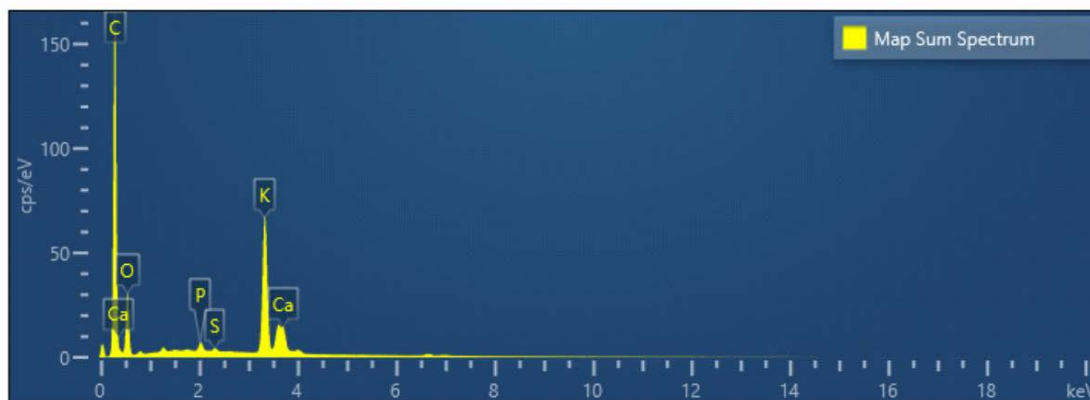


Figure 5: EDS from coffee parchment.

### 3.2 Pyrolysis Test Results

The temperature of the pyrolysis during the experiments was set at 350°C. Figure 6 illustrates the temperature progression at three distinct measuring locations: within the reactor ( $T_1$ ), the reactor wall ( $T_2$ ), and the outside furnace wall ( $T_3$ ). The locations of the three measurement points on the reactor are shown in Figure 2. In general, the temperature heating rate achieved by burning the LPG is only 4.5 °C/minute, which is included in the slow pyrolysis category (Hoang et al., 2021). It is apparent that the reaction temperature ( $T_1$ ) of 350°C was achieved after 80 minutes. At this temperature, the process was sustained for 1 hour and 30 minutes, constituting a total processing time of 180 minutes. Initially, the temperature at the reactor wall ( $T_2$ ) surpassed  $T_1$ , but after 70 minutes, it began to decline and fluctuated within the range of 291 to 320°C. This temperature variation is a result of exothermic reactions and heat buildup inside the reactor. Notably, maintaining the pyrolysis temperature was linked to the  $T_1$  reading by adjusting the LPG valve. On the upper side of the furnace wall ( $T_3$ ), the temperature ranged from 109 to 141°C after 60 minutes of operation. Calculations indicated a notable difference between  $T_2$  and  $T_3$ , yielding a furnace effectiveness value of 0.85. This demonstrates effective insulation, impeding heat transfer to the exterior (Nemati et al., 2024).

#### 3.2.1 Proximate, caloric value, and SEM analyses of Bio-char

The analysis results of proximate and caloric value of bio-char coffee parchment are shown in Table 5. The pyrolysis process, conducted at an operating temperature of 350 °C, yielded moisture and ash contents of 6.48% and 12.86%, respectively. These results align with earlier studies conducted under comparable conditions. (Kiggundu; Sittamukyoto, 2019). Conversely, the biochar exhibits a substantial volatile matter content of 38.63%, signifying its potential as a raw material for gasification and pyrolysis processes (Moreira et

al., 2017). The fixed carbon content has been determined to be 42.02%, with a calorific value of 24793 J/g for the biochar. These high values suggest that biochar holds potential as a solid fuel source (Rasaq et al., 2021).

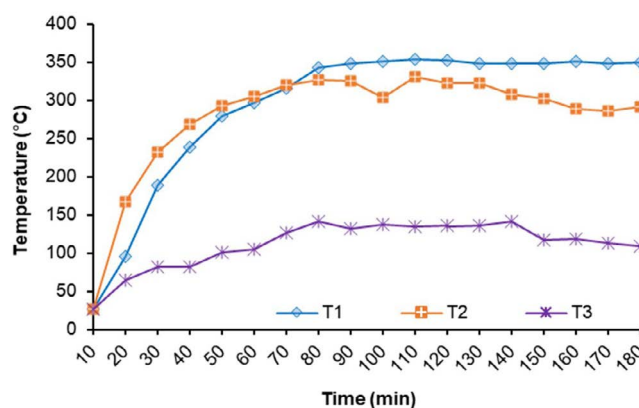


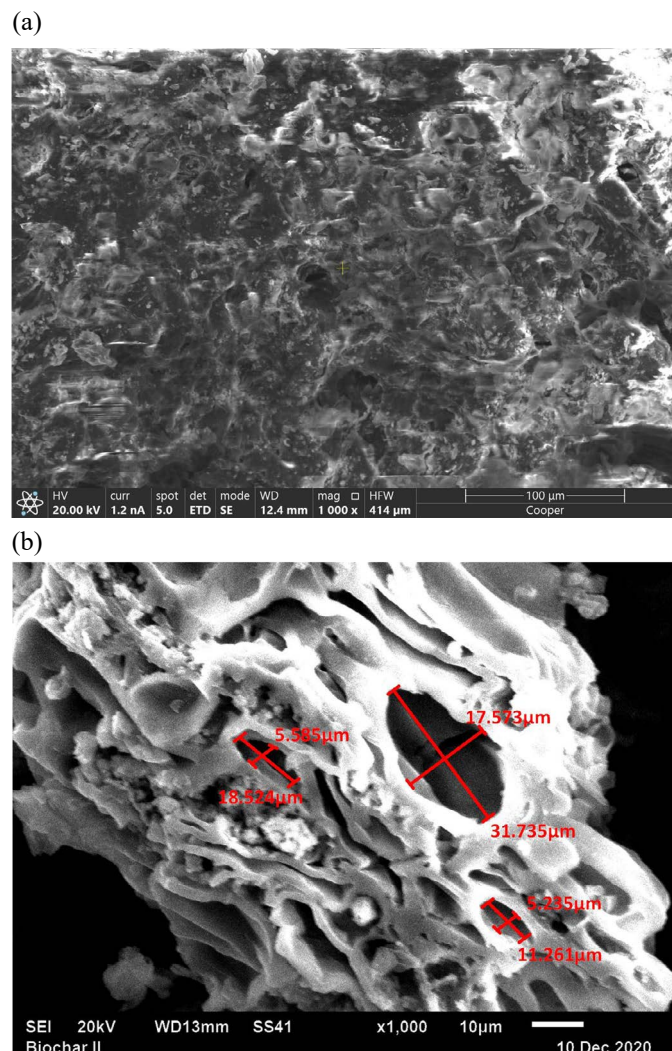
Figure 6: Pyrolysis reactor temperature profile

Table 5: Proximate and caloric value of coffee parchment bio-char.

| Parameter            | Value  |
|----------------------|--------|
| Moisture content (%) | 6.48   |
| Volatile Matter (%)  | 38.63  |
| Ash content (%)      | 12.864 |
| Fixed Carbon (%)     | 42.02  |
| HHV (J/g)            | 24793  |

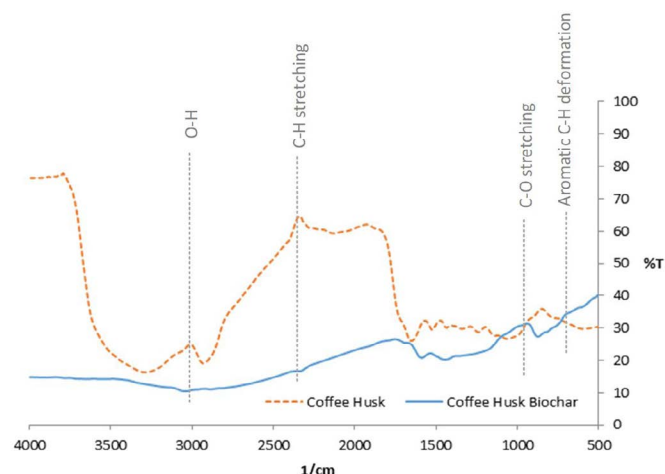
The SEM examination of the coffee parchment biomass (a) and the bio-char (b) is presented in Figure 7. The analysis was conducted at identical magnification levels, revealing a marked transformation in surface structure between these two images. Post-pyrolysis, the pore size notably increases.

The observed alterations in microstructure and topography primarily stem from the breakdown of organic and mineral components present in the biomass (Tabakaev et al., 2019).



**Figure 7:** SEM analysis: (a) Coffee parchment before pyrolysis, (b). Coffee parchment after pyrolysis.

Figure 8 displays FTiR spectra of coffee parchment raw material and biochar product. Within the spectra of Arabica coffee parchments, the O-H group at a wavelength of  $3034\text{ cm}^{-1}$  indicates an alcohol compound, stretching aliphatic groups ( $2928\text{--}2850\text{ cm}^{-1}$ ), C-H which indicates an alkane compound at a wavelength of  $2850\text{--}2960\text{ cm}^{-1}$  (Setter et al., 2020b). Meanwhile, after carbonization, the aliphatic group was stretched ( $2928\text{--}2850\text{ cm}^{-1}$ ) as well as the C-O bond ( $1030\text{ cm}^{-1}$ ) (Lopes, 2020). This is associated with oxygenated functional groups of cellulose, hemicellulose and methoxy groups of lignin. The loss of their intensity indicates a dehydration reaction and depolymerization of lignocellulosic components (Setter et al., 2020a).



**Figure 8:** FTIR spectra of Gayo Arabica coffee parchment and biochar.

### 3.2.2 Bio-oil composition and properties

As a by-product of the pyrolysis process, pyrolytic oil was collected both before and after passing through the condenser for further analysis. The characteristics of bio-oil and tar, including density, viscosity, and pH values, are presented in Table 6. The density, viscosity, and pH of bio-oil are recorded as  $1.01457\text{ g/cm}^3$ ,  $0.14\text{ mm}^2/\text{s}$ , and 4, respectively. In comparison, the density, viscosity, and pH of tar are  $1.01459\text{ g/cm}^3$ ,  $0.854\text{ mm}^2/\text{s}$ , and 4, respectively. Notably, there is no significant difference in the density between these liquids. However, the viscosity of tar is considerably higher compared to bio-oil, which has a relatively lower viscosity of  $0.14\text{ mm}^2/\text{s}$ . Both product types exhibit a fairly neutral pH condition.

The chemical composition of bio-oil and tar collected through Gas Chromatography-Mass Spectrometry (GC-MS) is shown in Table 7. Bio-oil and tar contain similar compounds, with caffeine and phenol being the main constituents. In bio-oil, caffeine constitutes 47.77%, and in tar, it accounts for 41.37%. Similarly, phenol comprises 13.33% in bio-oil and 13.04% in tar. The highest proportions of these compounds are predominantly present in bio-oil. On the other hand, tar exhibits higher percentages of 2,2-dimethoxybutane and 2-Furanmethanol (CAS) Furfuryl alcohol, amounting to 1.94% and 5.42%, respectively, compared to bio-oil, which has 1.79% and 5.35% of these compounds.

### 3.3 Economic Analysis

Economic analysis is widely used to assess innovative projects, with the Net Present Value (NPV) approach being a prominent and intricate method. This technique involves discounting all anticipated cash flows (both inflows and outflows) arising from the innovation project using a specified discount rate and aggregating them (Žižlavský, 2014). Various



parameters come into play in calculating business feasibility, including product sale price, annual operating days, and interest rate (Patel et al., 2018). Table 8 summarizes the parameter considered for this analysis.

**Table 6:** Properties of bio-oil and tar product.

| Sample                                   | Density (g/cm <sup>3</sup> ) | Viscosity (mm <sup>2</sup> /s) | pH  |
|--|------------------------------|--------------------------------|-----|
| Bio-oil collected before condenser (tar) | 1.01457                      | 0.814                          | 4.6 |
| Bio-oil collected after the condenser    | 1.01459                      | 0.854                          | 4.6 |

**Table 7.** Chemical composition of coffee parchment bio-oil and tar obtained from GC-MS.

| No  | Compound Name   | Percentage (%) |       |
|-----|---|----------------|-------|
|     |   | Bio-Oil        | Tar   |
| 1.  | Pyridine (CAS) Azine  | 5.75           | 5.23  |
| 2.  | Pyridine (CAS) Azine<br>1H-Pyrrole (CAS) Pyrrole                  | 2.54           | 1.86  |
| 3.  | 2,2 dimethoxybutane   | 1.79           | 1.94  |
| 4.  | 2-Furanmethanol (CAS) Furfuryl alcohol                            | 5.35           | 5.42  |
| 5.  | 2-Cyclopenten-1-one, 2-methyl- (CAS) 2                            | 1.32           | -     |
| 6.  | Phenol (CAS) Izal   | 13.33          | 13.04 |
| 7.  | 2,3-Dimethyl-2-cyclopentene-1-one                                 | 1.20           | -     |
| 8.  | Phenol, 2-methyl- (CAS) o-Cresol                                  | 9.20           | 8.44  |
| 9.  | Phenol, 2-methoxy- (CAS) Guaiacol                                 | 2.17           | 1.98  |
| 10. | 2(1H)-Pyridinone (CAS) 2-Pyridone                                 | 4.20           | -     |
| 11. | 3-Pyridinol, 2-methyl- (CAS) 3-Hydroxy-2-methylpyridine           | 2.84           | 3.03  |
| 12. | 2-Propenoic acid, 2-methyl-, ethyl ester (CAS) Ethyl methacrylate | 1.24           | -     |
| 13. | Daucol  | 1.32           | -     |
| 14. | Caffeine  | 47.77          | 41.37 |
| 15. | 3-Pyridinol (CAS) 3- Hydroxypyridine                              | -              | 5.37  |
| 16. | 2-Amino-5,6-Dihydro-4,4,6- Trimethyl -4H-1,3-Oxazine              | -              | 2.15  |
| 17. | 1-Buta-1,3- Dienyl -Pyrrolidine                                   | -              | 2.64  |
| 18. | 2,6-Dimethyl-3-hydroxypyridine                                    | -              | 2.15  |

**Table 8:** Parameter considered for economic analysis.

| Parameter                                  | Value  | Unit              |
|--|--------|-------------------|
| Annual operating days                      | 312    | Days/years        |
| Pyrolysis Capacity                         | 3      | Kg                |
| Yield of bio-char                          | 34.35  | %                 |
| Yield of bio-oil                           | 41.96  | %                 |
| Labor Monthly Rates                        | 183.10 | \$/m              |
| Biochar Sales Price                        | 0.70   | \$/kg             |
| Bio-oil Sales Price (Vasalos et al., 2016) | 1.03   | \$/kg             |
| Firing Cost                                | 0.42   | \$/kg             |
| Water cost (Vasalos et al., 2016)          | 0.06   | \$/m <sup>3</sup> |
| Plant Life                                 | 10     | Year              |
| Salvage Value                              | 10     | %                 |
| Interest Rate                              | 4      | %                 |



Figure 9 presents the NPV curve over the investment's economic lifespan. Income calculations are based on the sales of bio-char and bio-oil, with respective selling and production prices detailed in Table 6. Based on the calculation of NPV using the parameters in Table 8, it can be concluded that the business is economically feasible with an investment payback period of 7 years.

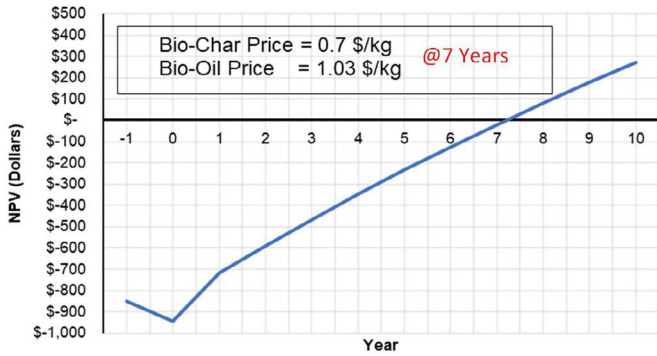


Figure 9: NPV throughout the economic life of the investment.

The impact of alterations in product selling prices on NPV was assessed, as illustrated in Figure 10. The NPV was subjected to variation by increasing and decreasing the selling price by 5% and 10%, a change that was applied to both bio-char and bio-oil products. The analysis demonstrated that NPV is highly responsive to shifts in the product selling price. For instance, a 10% increase in the selling price elevated the NPV at the end of the 10th year from \$172 to \$1810. Conversely, a 5% reduction in the selling price transformed a previously viable business unit, set to recoup capital by the 7th year, into an infeasible one.

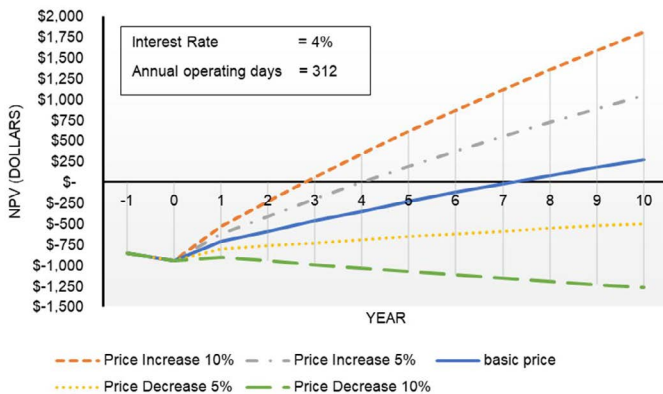


Figure 10: NPV with the variation of bio-char and bio-oil sale price.

Figure 11 depicts how alterations in the number of working days per year influence the NPV. For this simulation,

other parameters like product selling price, interest rate, investment life-time, and related factors are held constant. The calculation involves varying the working days from 290 to 330 days per year (varied in increments of 10 days). Based on the curves in Figure 11, it is evident that NPV is highly responsive to changes in the number of working days. A decrease in the annual working days from 312 to 300 renders the business financially unsustainable, resulting in continuous losses throughout the business's economic lifespan (10 years). Conversely, an increase in working days to 330 yields a rise in revenue by \$887 (from \$272 to \$1159).

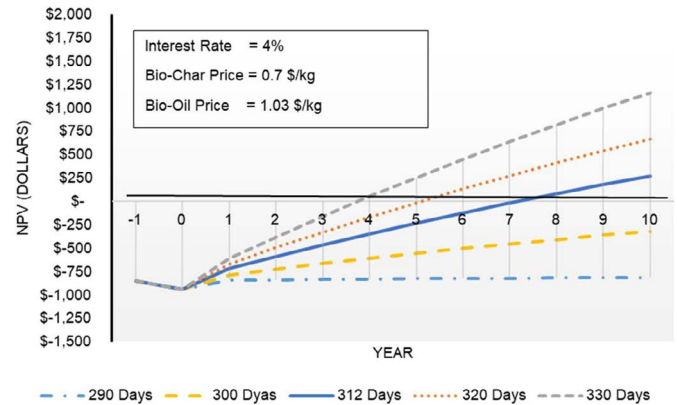


Figure 11: NPV with the variation of annual operating days.

The impact of fluctuations in the interest rate (IR) on NPV is presented in Figure 12. Interest rates range from 2% to 6%, incrementing by 1%, while maintaining other variables constant like product selling prices (\$0.7/kg for bio-char and \$1.03/kg for bio-oil) and working days (312 days per year). Figure 13 illustrates that alterations in the interest rate have minimal influence on NPV. The NPV value remains relatively stable, indicating no significant impact on the business unit's feasibility decision.

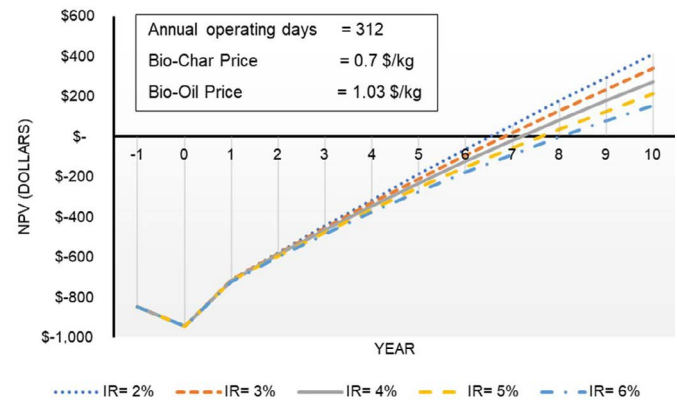


Figure 12: NPV with the variation of interest rate (IR).

The magnitude of a business's operations is a crucial factor to establish prior to its commencement. The scale of the enterprise significantly impacts investment outlay, operational expenses, and resultant revenue. The effect of business scale on NPV is shown in Figure 13. The simulation encompasses three levels of operational capacity: one unit, two units, and three units of pyrolysis reactors. Alterations in the quantity of pyrolysis equipment lead to augmented fixed costs like labor expenses and variable costs such as fuel and water expenditures. Consequently, a surge in earnings was observed owing to the amplified production of the products. The rise in the reactor units substantially augmented revenue, escalating from \$272 by the conclusion of year 10 (with one reactor unit) to \$7,298 (with two reactor units) and \$13,153 (with three reactor units).

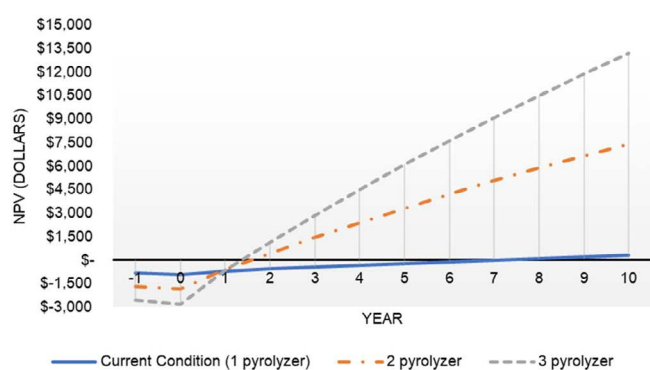


Figure 13: NPV with the variation of production scale.

## 4 DISCUSSION

The results of pyrolysis experiments conducted at 600°C and 5 bar pressure with coffee parchment can be categorized into three groups: bio-oil, biochar and pyro-gas. On average, the production yields were 34.5% bio-char, 42.15% bio-oil (comprising liquid smoke and tar), and 18.19% pyrolytic gas. These figures differ from the data published in initial studies on diverse biomass types. (Aysu et al., 2016; Biswas et al., 2017; Kiggundu; Sittamukyoto, 2019; Moreira et al., 2017; Setter et al., 2020a). The characteristics of biochar derived from this slow pyrolysis process yield superior results compared to torrefaction product. The utilization of a slightly higher reaction temperature at 350°C has enhanced the fixed carbon properties. In a related study (Matali et al., 2016). Torrefaction conducted at 300°C for *Leucaena Leucocephala* plants resulted in a torrefied biochar with a fixed carbon yield of only 30% wt.

The ultimate analysis results show that during combustion, the carbon and hydrogen constituents of biomass undergo exothermic reactions, producing CO<sub>2</sub> and H<sub>2</sub>O. Both carbon (C) and hydrogen (H) contents positively influence the

Higher Heating Value (HHV), while the presence of oxygen (O) has a negative impact. Additionally, hydrogen affects the Lower Heating Value (LHV) due to the formation of water. The sulphur content in coffee parchment is approximately 0.28%, and its adverse effect leads to the generation of SO<sub>x</sub> pollutants during combustion, causing corrosion to equipment. The nitrogen content is recorded at 1.04%, and high nitrogen levels pose a challenge for biomass fuel, resulting in the conversion to NO and, to a lesser extent, N<sub>2</sub>O during combustion. NO is a harmful pollutant causing direct damage to respiratory organs and acting as a precursor for acid rain and ground-level ozone. N<sub>2</sub>O is a potent greenhouse gas known for its role in stratospheric ozone depletion (Basu, 2010).

The FTIR spectrum also showed the carbonization process has formed aromatic C-H bonds at about 690-900 cm<sup>-1</sup>. This proves that carbonization increase aromatic compounds. These compounds are constituents of the hexagonal structure of carbon and activated carbon (Wibowo; Syafi; Pari, 2011). The existence of OH and C-O bond suggests that the resulting biochar possesses a higher polarity. Consequently, the biochar created holds promise for applications as an adsorbent for polar substances, potentially used in purifying water, refining sugar, processing alcohol, or even serving as a hydrogen storage materials (Wibowo; Syafi; Pari, 2011) The chemical composition of bio-oil and tar collected through Gas Chromatography-Mass Spectrometry (GC-MS) contains similar compounds, with caffeine and phenols as the main constituents.

## 5 CONCLUSIONS

The pyrolysis of Gayo Arabica coffee parchment was examined to unveil initial insights into its potential as a hydrogen storage material. Experiments conducted with pilot-scale reactors produced products comprising 34.5% bio-char, 42.15% bio-oil, and 18.19% pyrolytic gas. This indicates that coffee parchment holds promise as a suitable raw material for activated carbon production. The bio-char product exhibited a low water content (6.48%), a high carbon content (42.02%), and an elevated heating value of 24,793 J/g. In contrast, the bio-oil product had a density of 1.01 g/cm<sup>3</sup>, a viscosity of 0.14, and contained approximately 47.77% caffeine and 13.33% phenol. The equipment designed for the pyrolysis process of coffee parchment appears to be economically feasible for optimized annual operating days and for scaling up production.

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## 7 AUTHOR CONTRIBUTIONS

Conceptual idea: Setiawan, A; Muhammad.; Methodology design: Setiawan, A; Anshar, K.; Data collection: Sitepu, B.B; Riskina, S; Nurjannah, S.; Data analysis and interpretation: Setiawan, K; Muhammad; Hakim, L.; Writing and editing: Riskina, S; Nurjannah, S; Anshar, K.

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