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Assessing the Energy Profitability of Biofuels Generated from Coffee Waste via Microwave Pyrolysis

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The potential of coffee waste to be valorised into useful bioenergy is investigated using a continuous microwave pyrolysis rig. Coffee waste of Arabica species was ground and pretreated prior to pyrolysis at elevated temperature under CO2 atmosphere. Valorisation of the coffee waste result in char, liquid, and gaseous products. Analysis shows that biochar yield is highest at 450 °C, while bio-oil recovery peaks at 550 °C. Gaseous product results in highest yield at 650 °C. Energy analysis indicates that biochar contains the highest energy density, while bio-oil's energy density decreased with temperature due to cracking of volatiles. Energy profitability was shown to be negative across all temperatures, with highest deficit at 450 °C due to the formation of non-recoverable products such as water. Higher energy profitability was achieved at 650 °C as more volatiles could be recovered in gaseous form. The study shows that microwave pyrolysis is effective in valorising coffee waste and essential to enhance the energy recovery from coffee waste.

1. Introduction

Coffee is one of the most widely consumed beverages globally with significant economic value. With millions of cups consumed daily, coffee ranks as the second most favoured drink after water and stands as the second most traded commodity following petroleum (Lee et al., 2021). The coffee industry produced substantial amounts of waste that often end up in landfills that poses environmental concerns such as groundwater contamination, pollution from polyphenols, tannins, and caffeine, and requiring considerable space for disposal (Sermyagina et al., 2021). Each tonne of processed green coffee yields approximately 650 kg of coffee waste, leading to the accumulation of dark coloured waste (Mata et al., 2018). During the 2020-2021 period, global coffee consumption reached nearly 10 M t, leading in the production of about 6.5 M t of coffee waste (Ordieres and Cultrone, 2022). Microwave pyrolysis is a highly developed thermochemical process that break down biomass into biogas, bio-oil, and biochar without the presence of oxygen. This method is particularly advantageous as it achieves high fuel conversion efficiency up to 95.5 % and prevents the primary pollutants such as volatile organic compounds (VOCs), carbon monoxide (CO), and particulate matter (PM) undergo chemical reactions, leading to the formation of secondary pollutants. Utilising coffee waste as a feedstock for biofuel production offers the added benefit of not competing with food supplies and also provides an environmentally friendly substitute traditional lipid source such as soybeans and rapeseed. Prior research has demonstrated the feasibility of converting various types of waste into biofuels through pyrolysis. Horse manure pyrolysis in a microwave has been recorded to yield a negative energy profit due to the presence of non-energetic products such as water (Mong et al., 2020). Empty fruit bunches by microwave pyrolysis results in an overall energy deficit of -81.17 %, primarily due to its higher oxygen content. In contrast, waste tire valorisation by microwave pyrolysis achieves a 20.66 % total energy profit because the raw feedstock has a high calorific value (Mong et al., 2022). Despite these findings, there is a notable lack of data on the microwave pyrolysis of

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coffee waste, particularly concerning its energy recovery potential. Hence, this study focuses on evaluating the pyrolysis characteristics of coffee waste, the yield and energy content of the pyrolysed products, and the overall energy profitability of the thermochemical conversion process.

2. Material and methods

2.1 Feedstock preparation and characterisation

In this study, coffee waste of Arabica species was collected from a local café located in Pudong, Shanghai, China. The collected sample was evenly distributed on a metal pan and dried at a temperature of 60 °C for 36 h in a furnace. The specific drying temperature was selected to prevent the breakdown of lipids which can occur at temperatures exceeding 60 °C because of the fatty acid oxidation. Additionally, maintaining this temperature inhibits the growth of mould during the storage phase. The coffee waste exhibited a moisture loss of 13.68 wt% after drying. Characterisation of coffee waste was performed via ultimate analysis. The ultimate analysis was performed using an elemental analyser (Elementar, UNICUBE) to determine the proportions of sulphur, nitrogen, oxygen, hydrogen and oxygen in the sample.

2.2 Operating condition and test apparatus

Microwave pyrolysis of coffee waste was performed using a continuous microwave pyrolysis device (CY-CP1100C-S model). The microwave pyrolysis device is shown in Figure 1. The main component of the microwave pyrolysis reactor consists of a microwave generator that operating at a frequency 2.45 GHz with a maximum output power 7 KW. A quartz-glass reactor, measuring 450 mm in height and 60 mm in diameter, was used to hold the feedstock inside the microwave cavity. The coffee waste with a consistent weight of 100 g is transported forward by the rotary screw that maintain the rotational speed of the screw at 3 r/min to ensure a consistent residence time of the coffee waste within the microwave pyrolysis zone are and a stable processing speed. The microwave pyrolysis reaction is carried out under CO_2 atmosphere to maintain inert condition at the controlled flow rate of 2 L/min. The precise control was facilitated by a rotary flowmeter controller. The microwave pyrolysis was conducted at the temperature was set at the temperature of 450 °C, 550 °C, and 650 °C. Each run of the pyrolysis process was conducted for 1 h.

A flask under the condenser was used to collect the condensed vapour, which is the liquid product (bio-oil). In the meantime, moisture was removed by passing the uncondensed vapour over the silica gel bed. The resulting dry gases were collected in a gas bag for further analysis. The solid product was collected after the pyrolysis process for analysis. The condensed liquid product is purified via a filtration process to remove any solid residues or impurities prior to analysis.

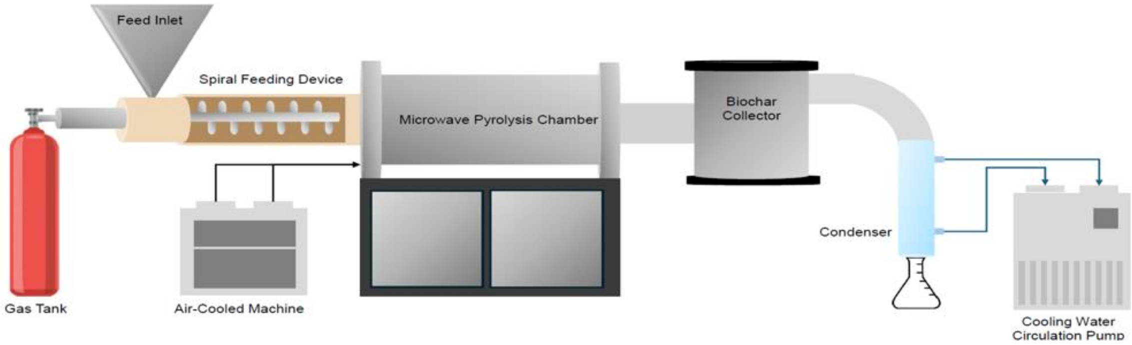

Figure 1: Microwave pyrolysis device schematic diagram

2.3 Characterisation of biofuel

The gravimetric approach was employed to quantify the product yields produced from the microwave pyrolysis process. The bio-oil collected in a flask and solid yield were quantified with a weight balance. To quantify the gas yield, a mass balance equation Eq(1) was utilised to quantify the end products.

$$Product\ yield\ (wt\%) = \frac{End\ product\ (kg)}{Feedstock\ (kg)} \times 100\ \% \quad (1)$$

The biogas produced utilised a gas chromatograph for analysis (Agilent GC 8860). The analysis allowed for the detection of various gaseous compounds such as CO, N_2, O_2, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_6, C_3H_8, C_4H_8 and C_5H_{12} are detected. The high heating value of the biogas is calculated by using Eq(2).

$$HHV_{GAS}\left(\frac{MJ}{Nm^3}\right)=\frac{(12.63\times Y_{COmol}+12.75\times Y_{H2mol}+39.82\times Y_{CH4mol}+63.43\times Y_{C2-C5mol})}{100} \quad (2)$$

where $Y_{C2\text{-}C5,mol}$, $Y_{CH4,mol}$, $Y_{H2,mol}$, and $Y_{CO,mol}$ are the molar fractions of C_2-C_5 compounds, methane, hydrogen, and carbon monoxide.
The energy content of the biogas is calculated by aggregating the energy content of individual gas species based on the volume via Eq(3).

$$Gaseous\ Product\ Energy\ (MJ)=Product\ HHV\left(\frac{MJ}{m^3}\right)\times Gas\ Volume\ (m^3) \quad (3)$$

The elements that make up the bio-oil including hydrogen, carbon, nitrogen, sulphur, and oxygen, was analysed using an elemental analyser (Elementar, UNICUBE). These values were then used to determine the higher heating value (HHV) of the liquid product as shown in Eq(4).

$$HHV_{LIQUID}\left(\frac{MJ}{kg}\right)=\frac{(124.3\times H+34\times C+6.3\times N+19.3\times S-9.8\times O)}{100} \quad (4)$$

A bomb calorimeter (SDC 712) was used to measure the heating value of solid product (biochar) heating value. The product energy of the liquid and solid product is calculated using Eq(5) which considers the product yield (wt%) and the higher heating value (HHV) of each product.

$$Product\ Energy\ (MJ)=Product\ HHV(MJ/kg)\times Product\ yield(wt\%)\times Feedstock(kg) \quad (5)$$

The energy profit is calculated using Eq(6) that involves summing the energy values of the solid, liquid and gas products and comparing them to the initial feedstock energy to determine the overall profitability of the biofuel production process.

$$Energy\ Profit\ (\%)=\frac{\sum Product\ Energy\ (MJ)-Feedstock\ Energy(MJ)}{Feedstock\ Energy(MJ)}\times 100\ \% \quad (6)$$

3. Result and discussion

3.1 Feedstock physiochemical properties

Table 1 shows the ultimate analysis of coffee waste. The ultimate analysis indicates that coffee waste has a high content of carbon (46.11 wt%) and oxygen (46.05 wt%), while hydrogen (5.73 wt%), nitrogen (1.97 wt%) and sulfur (0.14 wt%) constitute the rest. The high carbon and oxygen content in the coffee waste is attributed to the high lignocellulosic content, making it a potential feedstock for product valorisation via thermochemical conversion. Lo et al. (2017) reported that coffee waste has carbon (44.89 wt%), hydrogen (6.14 wt%), nitrogen (0.35 wt%), and oxygen (48.62 wt%) with an HHV of 16.78 MJ/kg. The measured higher heating value of the coffee waste prior to pyrolysis is 18.44 MJ/kg, which is comparable to other biomass such as paper film (18.1 MJ/kg) (Yang et al., 2017), corn stover (16.82 MJ/kg) (Cong et al., 2018), and rice straw (16.16 MJ/kg) (Lo et al., 2017). The HHV value of coffee waste falls within the typical HHV range of crude biomass which is between 15 and 20 MJ/kg (Chen et al., 2015). These comparisons indicate the potential of coffee waste as feedstock. However, the nitrogen content in coffee waste is slightly higher compared to most energy crops and fossil fuels which typically have nitrogen contents below 1 wt% (Ebeling et al., 1985). The sulfur and nitrogen content in coffee waste is in trace amount, which is advantageous for the bio-oil and syngas production via thermochemical conversion, as these compounds will not migrate and contaminate the bioproducts. Thus, low emissions of SO_x and NO_x can be expected when using these products as fuel (Mong et al., 2019).

Table 1: Physiochemical properties of coffee waste sample

Ultimate Analysis (wt%)	
Carbon	46.11
Hydrogen	5.73
Oxygen	46.05
Nitrogen	1.97
Sulphur	0.14

3.2 Product yield

Figure 2 shows the product yield generated by microwave pyrolysis of coffee waste at a constant CO_2 flow rate of 2 L/min, and at different pyrolysis temperatures. At pyrolysis temperature of 450 °C, the yield of biochar is highest at 42 %, followed by bio-oil at 34 %, and biogas at 24 %. As the temperature rises to 550 °C, the biochar yield remains relatively constant at 43 %, while the bio-oil yield peaks at 42 %, and the biogas yield decreases to 15 %. At the elevated temperature of 650 °C, the biogas yield increases significantly to 43.20 %, the yields of biochar and bio-oil decrease to 33 % and 23.80 %. These observations indicate that higher pyrolysis temperatures favor the production of biogas, while lower temperatures are more conducive to biochar production. The peak bio-oil yield at 550°C suggests that this temperature is optimal for maximising bio-oil production.

The observed trends are aligned with the results reported by Jouhara et al. (2018), in which the yield of biochar decreases with increasing temperatures. The temperature at which pyrolysis occurs is 450 °C, the energy supplied is insufficient to fully decompose the coffee waste, resulting in higher yield of biochar caused by the carbonisation process (Setter et al., 2020). The rising in biogas yield at higher temperatures is attributed to secondary reactions such as decarboxylation, dehydration, and condensation of pyrolytic vapors, which convert bio-oil into smaller gaseous compounds. The yield of bio-oil increases with temperature elevation from 450 °C to 550 °C. This increase is due to the primary decomposition of cellulose, hemicellulose, and lignin within the coffee waste. However, further heating to 650 °C results decrease in bio-oil yield, which is likely due to secondary reactions that convert bio-oil into smaller gaseous compounds.

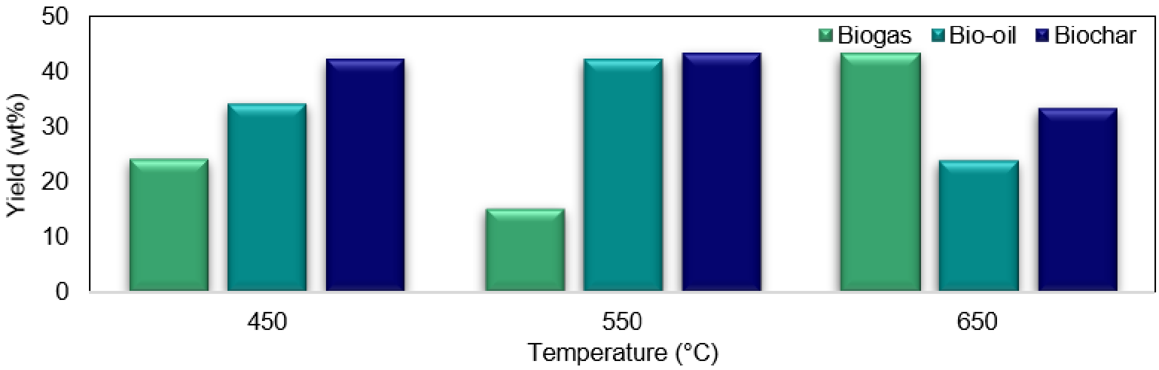

Figure 2: Product distribution from coffee waste microwave pyrolysis carried out at various temperatures.

3.3 Analysis of energy recovery

The energy density of the pyrolysed products from coffee waste via microwave pyrolysis were determined to assess their potential as biofuels. Figure 3 illustrates the higher heating value (HHV) of the biogas, bio-oil and biochar at different pyrolysis temperatures. The results indicate that biochar consistently exhibits a significantly higher HHV compared to biogas and bio-oil. Specifically, the HHV of biochar increases from 26.7 MJ/kg at 450 °C to 28.3 MJ/kg at 650 °C. This increase in energy density with temperature due to the use of CO_2 carrier gas promotes the carbonisation process, which reduces the carbon proportion in carboxylate species and raises the aromatic carbon content in the biochar, thereby enhancing its thermal stability (Wang et al., 2022). These chemical processes generate a dry and dense carbon structure by breaking down the functional groups that include oxygen and developing alkyl-aryl C-C bonds. In comparison, other biomass sources such as canola straw and wheat straw exhibit energy density ranging 22.3-26.9 MJ/kg (Nzediegwu et al., 2021). Biochar derived from microwave pyrolysis of coffee waste contains high energy density, making it a potential solid fuel with high energy content.

The bio-oil exhibits peak energy density at 450 °C. As the temperature rises, the energy density in bio-oil decreases due to the increased cracking of volatiles, which reduces the presence of heavier compounds in the liquid yield. The product distribution shifts towards gaseous product outputs at higher temperatures because the extra energy causes further volatiles to break and decompose into light hydrocarbon gases. The lower heating value of bio-oil from CO_2 pyrolysis is attributed to the presence of water within bio-oil that formed due the water-gas shift reaction ($H_2 + CO_2 \rightarrow H_2O + CO$). High concentrations of CO_2 in the pyrolysis atmosphere have the potential to react with hydrogen molecules to produce water and CO (Mong et al., 2022). Despite its lower calorific value, coffee waste derived bio-oil mainly contains oxygenated compounds such as ketones, phenols and pyridine that can be extracted for biochemical production (Del Pozo et al., 2020). The presence of oxygenated compounds in the bio-oil contributes to lower energy content in the liquid yield.

The energy density in biogas increases with rising pyrolysis temperatures, as higher temperature facilitates volatile substances to break down into smaller gaseous components and enhancing the energy density of the gaseous product. Higher temperatures favor the production of biogas with higher energy density, lower temperatures are more conducive in producing bio-oil with higher energy density. Biochar consistently demonstrates high energy density across all temperatures, making it a viable solid fuel option. This trend highlights the temperature as an important factor influencing the yield and energy density of the resulting products.

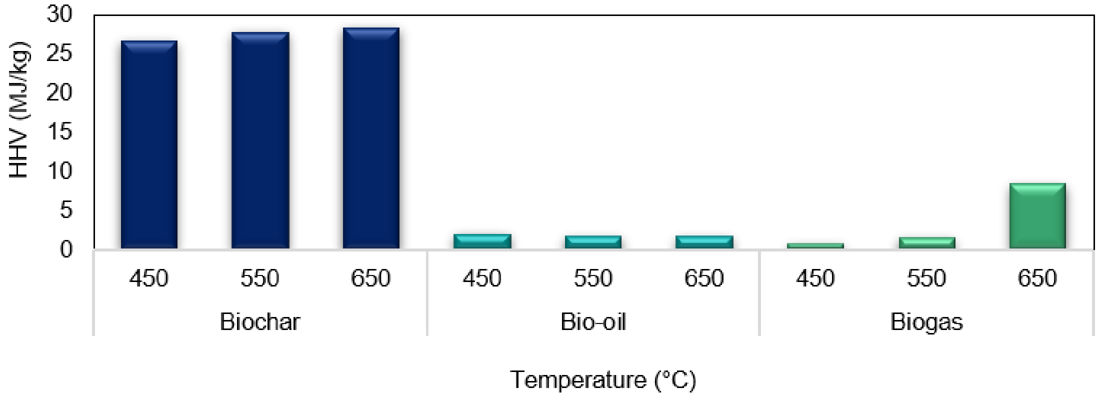

Figure 3: Higher heating value of products conducted at different pyrolysis temperatures.

By calculating the energy content of each pyrolysed product, the energy profitability of the microwave pyrolysis of coffee waste was determined. Figure 4 shows the energy profit radar plot for the pyrolysed coffee waste products at 450 °C, 550 °C, and 650 °C. The analysis reveals that all three cases result in negative energy profit, indicates that the overall energy in the final products is lower than the initial coffee waste. Among the tested temperatures, the highest energy profit occurs at temperatures of 650 °C. Conversely, a temperature of 450 °C shows the highest energy deficit. The energy deficit is partly due to the water formation which is a by-product and therefore not contributing to the energy profit. The generation of bio-oil containing high oxygenated compounds results in low heating value and reducing the energy density. The energy lost during microwave pyrolysis due to non-recoverable products such as water. In the case of coffee waste, the energy deficit ranges from -27 % to -34 %. Despite the negative energy profit, coffee waste shows promise as a biomass feedstock for energy production. The energy profitability is significantly influenced by the nature of the by-products formed and the pyrolysis conditions.

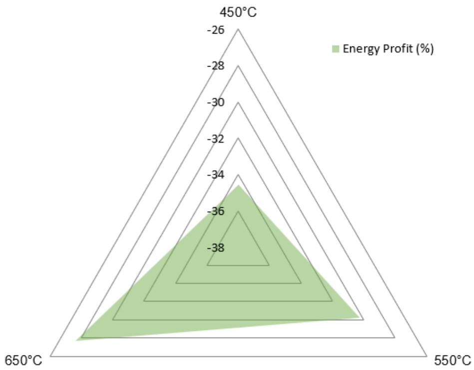

Figure 4: Energy profit for microwave pyrolysis of coffee waste at temperature of 450 °C, 550 °C and 650 °C.

4. Conclusions

This study examined the potential of coffee waste as a biomass feedstock for energy production through microwave pyrolysis. The ultimate analysis of coffee waste has a significant amounts of carbon and oxygen. The microwave pyrolysis process yielded biochar, bio-oil, and biogas with their respective yields varying according to the pyrolysis temperature. Biochar yield was highest at 450 °C, bio-oil yield peaked at 550 °C, and biogas yield increased significantly at 650 °C. The energy density analysis indicated that biochar consistently exhibited the highest energy density, making it a viable solid fuel. However, the analysis revealed a negative energy profit across all tested temperatures, with the highest energy deficit observed at 450 °C and the highest energy profit at 650 °C. The energy deficit was primarily due to the formation of non-recoverable products such as water, which absorb heat and reduce the overall energy output. The findings highlight that both the pyrolysis temperature and the composition of the feedstock are critical factors influencing the energy efficiency and profitability of the process. Despite the current challenges, coffee waste shows promise as a sustainable biomass feedstock for clean energy production, offering a potential alternative to solid fossil fuels.

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