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Evaluation of Biochar Production from Waste Sources for Syngas Production

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ABSTRACT

This research examines the viability of producing syngas by CO_2 gasification of biochar obtained from chicken bone waste (CBW) and empty fruit bunch (EFB), two prevalent waste materials in Malaysia. Agricultural and poultry waste provides significant national environmental concerns, underscoring the pressing need for sustainable energy solutions and effective waste management measures. This study aims to analyse the chemical properties of biochar derived from CBW and EFB and evaluate their potential for syngas generation. Biochar was produced by pyrolysis and subsequent gasification, with the resultant gases analysed using Fourier Transform Infrared Spectroscopy (FTIR) and Thermogravimetric Analysis coupled with Mass Spectrometry (TGA-MS). The FTIR study indicated a decrease in hydroxyl and aliphatic groups in both biochar types of post-pyrolysis, implying an enhancement in carbon content and structural simplicity. Thermogravimetric Analysis (TGA) research revealed that CBW biochar had more weight loss than EFB biochar during gasification, indicating superior thermal breakdown characteristics and enhanced reactivity. Mass spectrometry (MS) investigation of CO_2 gasification products from chicken bone waste (CBW) and empty fruit bunch (EFB) biochar revealed that both biochar produces essential syngas constituents—hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4). EFB biochar generated elevated hydrogen concentrations, exhibiting ion currents of 7.85×10^{-9} A at m/e = 2 and 1.14×10^{-10} A at m/e = 4, in contrast to CBW biochar, which displayed 6.00×10^{-9} A and 7.21×10^{-11} A. Both biochar emitted considerable quantities of CO and CO_2, with EFB biochar exhibiting somewhat elevated levels for both gases. Furthermore, EFB biochar exhibited a higher methane emission. This data indicates that CBW biochar is more appropriate for long-term gasification, whereas EFB biochar is more effective for rapid gas production. The results of this study suggest that biochar produced from chicken bone waste and empty fruit clusters could be a viable feedstock for syngas generation, providing a sustainable alternative to renewable energy production. Future research should concentrate on augmenting the catalytic characteristics of biochar and investigating its incorporation into renewable energy systems to enhance sustainability and waste management techniques.

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1. Introduction

The world's energy consumption is growing at an accelerated rate, which emphasises how urgently clean and renewable energy sources are needed. Malaysia is projected to have a 60% rise in energy demand by 2050, accumulating 6.7 exajoules [15]. Presently, more than 95% of Malaysia's energy supply is dependent on fossil fuels [9], which substantially contributes to greenhouse gas emissions, including carbon dioxide (CO_2) [10], and exhausts limited natural resources. This scenario highlights the need for new strategies to address energy requirements while reducing environmental effects.

Concurrently, Malaysia produces over 38,000 metric tonnes of solid waste per day [6], with the agriculture and poultry sectors contributing a significant amount of this waste. Some contributors to this waste are empty fruit bunches (EFB) from palm oil production and chicken bone waste (CBW) from the poultry sector. The poultry sector in Malaysia is seeing tremendous growth, generating substantial amounts of CBW. Malaysians, consuming around 50 kg of chicken per capita per year, are the foremost poultry eaters in Asia [8]. The sector fulfils 98.4% of the nation's chicken meat demand [8], demonstrating the substantial availability of CBW for potential value-added applications.

Traditional methods for disposing chemical and biological waste, such as landfills or repurposing as animal feed, are environmentally unsustainable and economically impractical [16]. In a similar vein, inadequate management of EFB intensifies environmental issues. Recent research has examined the transformation of biomass waste into high-value products by thermochemical processes, including pyrolysis. EFB, a lignocellulosic material composed of cellulose (20–50%), hemicellulose (23–36%), and lignin (22–51%) [20], may be transformed into biochar, a substance recognised for its use in agriculture and energy production.

Furthermore, the worldwide production of municipal solid waste (MSW) persists in increasing due to population expansion, urbanisation, and improved living conditions [5]. The improper disposal of organic waste contributes to environmental contamination and signifies a lost chance for resource recovery. In Malaysia, incorporating waste-to-energy technology may resolve waste management issues while satisfying the growing energy demand [5].

The present study examines the viability of using CBW and EFB as feedstocks for biochar formation and syngas generation via CO_2 gasification to address these interconnected concerns. Although biochar has advantages for soil enhancement and carbon sequestration [18], its capacity as a fuel for syngas production by CO_2 gasification is yet inadequately investigated. This study addresses this gap by characterising biochar obtained from various waste sources and assessing its efficacy in syngas generation.

Advanced characterisation methods, such as Fourier Transform Infrared Spectroscopy (FTIR) and Thermogravimetric Analysis combined with Mass Spectrometry (TGA-MS), were used to examine biochar's functional groups, thermal stability, and gasification behaviour. The results provide essential insights for improving biochar for CO_2 gasification, aiding Malaysia's National Energy Transition Roadmap (NETR) in mitigating greenhouse gas emissions in accordance with the Paris Agreement [5].

This work tackles urgent environmental and energy issues in Malaysia by transforming biomass waste into sustainable electricity. It offers a novel approach to waste management and energy sustainability, aiding in achieving global environmental and energy objectives.

2. Methodology
2.1 Preparation of Feedstock Material

The experiment used materials derived from two types of waste: chicken bone waste (CBW) and empty fruit bunch (EFB). The CBW was acquired from leftover student meals in the Kolej Siswa Jaya cafeteria, Universiti Teknologi Malaysia Kuala Lumpur. It was thoroughly cleansed to remove leftover tissue and then air-dried [3]. The EFB was obtained from a palm oil facility situated in Felda Inas, Johor. It underwent a comprehensive cleaning procedure to ensure it was devoid of impurities. The desiccated CBW and EFB were ground and sieved to get particle sizes between 180 and 250 µm [22]. The materials were stored in sealed containers to inhibit moisture and fungal growth prior to pyrolysis.

2.2 Pyrolysis Process

Pyrolysis involves the thermal decomposition of organic substances in the absence of oxygen [2]. The raw materials were converted into biochar using a microwave-assisted pyrolysis method. The laboratory setup included a modified domestic microwave oven (Samsung, 1 kW, 2.45 GHz) fitted with a quartz reactor and a Liebig condenser connected to a water chiller. The pyrolysis experiments used around 5 grammes of CBW or EFB samples and 1.25 grammes of activated carbon (AC) as a microwave absorber [1]. An inert environment was created by cycling nitrogen gas (N_2) through the reactor at a flow rate of 1 L/min for 30 minutes before pyrolysis. The reactor operated at a power output of 450 watts for a duration of 10 minutes [1]. After cooling, the biochar underwent filtration to isolate the activated carbon (AC).

2.3 Characterisation of Biochar by Chemical Properties Analysis

The functional groups in the biochar samples were identified using the Fourier Transform Infrared (FTIR) spectroscopy (PerkinElmer Frontier 104968) with a resolution of 4 cm^{-1}, averaging thirty-two scans. Spectra were obtained within a wavelength range of 4000 cm^{-1} to 500 cm^{-1} [22] to determine the biochar's chemical structures.

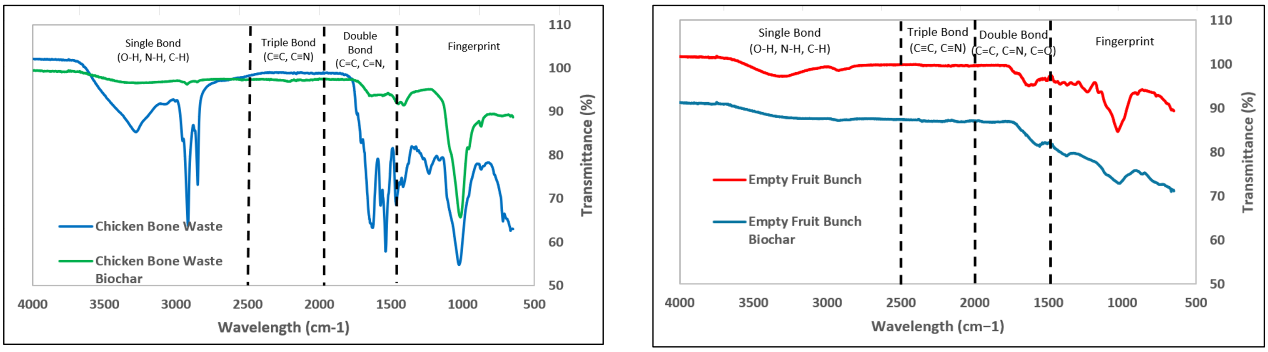
2.4 Gasification Process for Syngas Production for Gas Composition Evaluation

The biochar's thermal stability and gas evolution characteristics during CO_2 gasification were analysed using the thermogravimetric analyzer combined with mass spectrometry (TGA-MS). With a nitrogen (N_2) flow of 30 ml/min and a heating rate of 15°C/min, the temperature of the biochar sample was progressively raised to 850°C [4]. The material was maintained at 850°C for 20 minutes to remove volatile chemicals. Subsequently, N_2 was substituted by CO_2 at a 30 ml/min flow rate, and the sample was subjected to CO_2 gasification for up to 90 minutes [4]. This setup made conducting a comprehensive assessment of syngas production capacity and gasification efficiency easier.

3. Results
3.1 Characterisation of Biochar by Chemical Properties Analysis

Figure 1 illustrates the Fourier Transform Infrared Spectra (FTIR) for chicken bone waste (CBW), CBW biochar, empty fruit bunch (EFB), and EFB biochar, examined within the wavelength range of

4000 – 500 cm^{-1}**.** The spectra show various absorbance peaks corresponding with specific functional groups in the samples.



(a) (b)

Fig. 1. FTIR spectra of chicken bone waste (CBW) and CBW biochar (left) and empty fruit bunch (EFB) and EFB biochar (right)

The FTIR research provides significant insights into biochar's chemical composition and structural changes derived from chicken bone waste (CBW) and empty fruit bunch (EFB). These findings underscore the chemical alterations induced by pyrolysis, which are crucial for evaluating the efficacy of biochar in gasification.

According to Nandiyanto *et al*., [21] the FTIR spectra of CBW have a large absorption band between 3650 and 3250 cm^{-1}, associated with hydroxyl (-OH) groups, most likely originating from water or organic substances. The peaks at 2935 and 2860 cm^{-1} signify aliphatic C-H stretching, indicative of aliphatic molecules. Absorption bands in the 1750-1700 cm^{-1} range indicate the presence of carbonyl (C=O) groups, including ketones, aldehydes, esters, or carboxyl groups. Moreover, the fingerprint area (600-1500 cm^{-1}) has several peaks linked to the bending vibrations of -CH_2- and -CH_3 groups, C-O stretching, and C-H bending [17], indicating the chemical complexity of the raw material.

Conversely, the FTIR spectrum of CBW biochar displays fewer and more pronounced absorption bands, indicating a more simplified molecular structure due to heat degradation during pyrolysis. The lack of a broad absorption band in single bonds (3650-3250 cm^{-1}) indicates the significant reduction of hydroxyl and carbonyl groups, implying moisture extraction and chemical degradation, although the persistence of some aliphatic features signifies partial retention of carbonaceous structures. These modifications improve the stability of biochar and decrease its moisture content, increasing its efficacy for gasification by minimising energy loss throughout the process [4].

The FTIR spectra of EFB and its biochar exhibit notable chemical alterations. The EFB spectra have a broad absorption band of about 3400 cm^{-1}, signifying the presence of hydroxyl groups from water or alcohols. Peaks slightly below 3000 cm^{-1} indicate aliphatic C-H stretching, signifying long-chain hydrocarbons. Carbonyl groups (C=O) and perhaps aromatic rings or alkenes are seen in the 1600-1700 cm^{-1} range, but the fingerprint area reveals many complex organic compounds, including C-O stretching about 1030 cm^{-1} [21]**.**

The EFB biochar spectrum has a reduced band around 3400 cm^{-1}, indicating dryness and the depletion of hydroxyl groups during pyrolysis. The decreased strength of the aliphatic C-H stretching bands under 3000 cm^{-1} suggests the degradation of long-chain hydrocarbons, whilst the peaks within the 1600-1700 cm^{-1} range signify alterations in carbonyl and aromatic structures. The fingerprint area retains functional groups, although their diminished intensity indicates a more simplified structure with fewer oxygen-containing molecules [21].

The FTIR research indicates that pyrolysis substantially alters the chemical structure of CBW and EFB, simplifying their molecular structure and improving stability. These modifications enhance the biochar's appropriateness for gasification by reducing its moisture content and increasing thermal efficiency [11], making it a desirable feedstock for renewable energy applications.

3.2 CO_2 Gasification Process for Syngas Production

3.2.1 Thermal stability and weight loss analysis of chicken bone waste biochar and empty fruit bunch biochar

Figure 2 and Figure 3 illustrate the TGA curve, which shows the weight loss of CBW biochar and EFB biochar when subjected to heating from ambient temperature to 850°C in an N_2 and CO_2 environment, respectively. Multiple discrete stages of weight loss can be identified, indicating various phases of thermal decomposition and gas release.

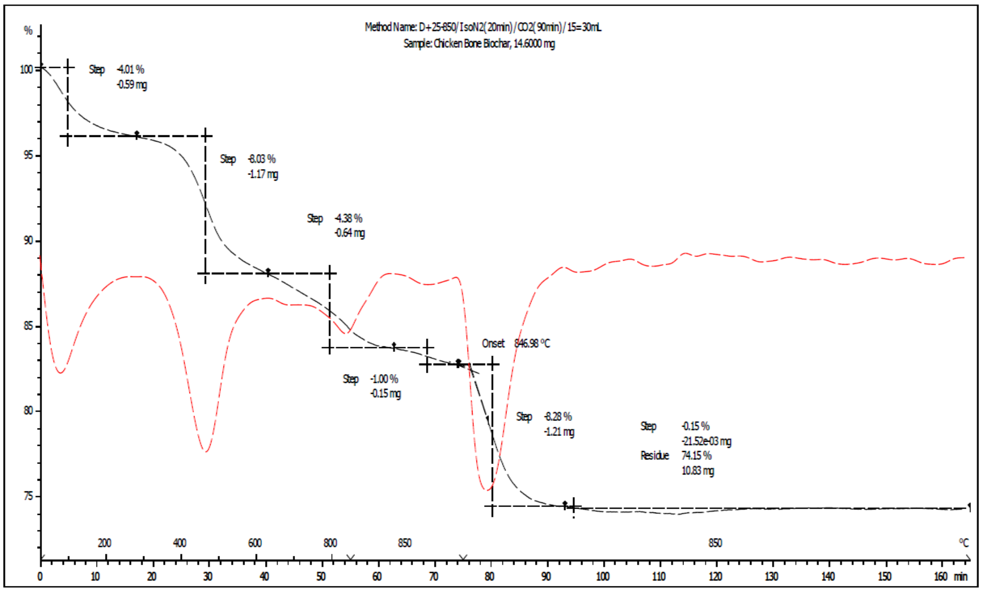


Fig. 2. Thermogravimetric analysis (TGA) of chicken bone waste biochar with a heating rate of 15 °C/min

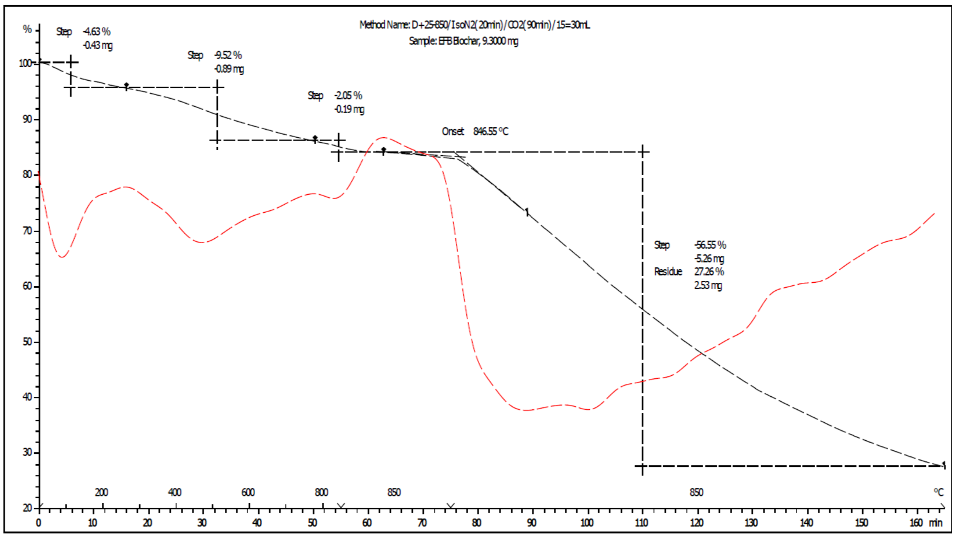


Fig. 3. Thermogravimetric analysis (TGA) of empty fruit bunch biochar with a heating rate of 15 °C/min

Thermogravimetric analysis (TGA) of CBW biochar demonstrates several stages of mass reduction, indicating its thermal degradation characteristics. At lower temperatures, a 4.01% reduction in weight occurs, primarily due to moisture evaporation and the release of volatile chemicals ((Hart et al. 2022)). Additional weight decreases are seen at 300°C (8.03%), 600°C (4.38%), and 850°C (1.00%), corresponding to the progressive decomposition of organic substances. At higher temperatures, notably over 800°C, weight losses of 8.28% have been observed, indicating the decomposition of highly stable organic compounds and the last stages of carbonisation [14]**,** resulting in a final residue of 74.15% (10.83mg). This significant residue signifies a high fixed carbon concentration, making CBW biochar very efficient for prolonged gasification operations. Its improved stability guarantees steady syngas generation, even throughout extended operating durations.

On the other hand, the TGA of empty fruit bunch (EFB) biochar shows a weight decrease of 4.63% at about 100°C, which is associated with the evaporation of volatile compounds and moisture. At 300°C, a 9.52% weight loss is observed, related to the breakdown of hemicellulose and cellulose [12]. A modest decline of 2.05% at 600°C signifies the destruction of more robust organic components, whilst the most pronounced weight loss of 56.55% transpires at 800°C due to the decomposition of lignin and other stable organic molecules [12]. The remaining 27.26% (2.53 mg) indicates a significant fixed carbon content, suggesting the possibility for syngas production during CO_2 gasification.

The TGA results highlight the distinct thermal stability and breakdown characteristics of CBW and EFB biochars, which are crucial for efficient CO_2 gasification. The increased fixed carbon concentration and reduced weight loss of CBW biochar augment its stability, making it ideal for prolonged gasification and reliable syngas generation. On the other hand, EFB biochar displays strong reactivity and efficient gas release due to its quick breakdown.

These data underscore the distinct benefits of each biochar type for syngas generation. CBW biochar is more appropriate for extended gasification owing to its enhanced stability, while EFB biochar is preferable for rapid gasification procedures. However, the study's focus on laboratory-scale studies and the restricted analysis of ash content and catalytic effects suggest that more research is necessary. Subsequent research should prioritise the expansion of experiments, the analysis of ash's catalytic characteristics, and the execution of long-term evaluations of environmental effects. In conclusion, CBW biochar offers increased stability and high fixed carbon content, while EFB biochar provides rapid reactivity, which is essential in improving biochar applications in sustainable energy and waste management.

3.2.2 Mass Spectrometry (MS) Analysis of Gas Evolution

The mass spectrometry (MS) measurements of empty fruit bunch (EFB) and chicken bone waste (CBW) biochar during CO_2 gasification are shown in Figure 4. The data indicates variations in ion current (A) across distinct mass-to-charge ratios (m/e), offering significant insights into both biochars' chemical processes and gas release characteristics during gasification.

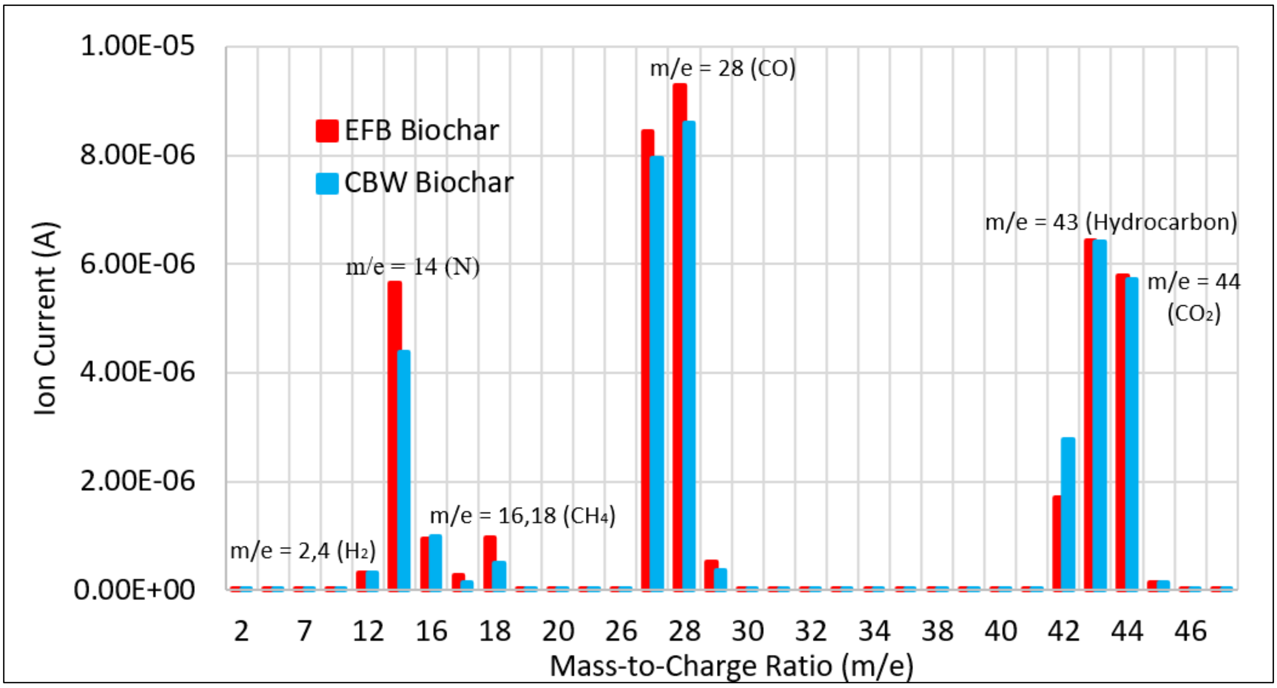


Fig. 4. Comparison of Ion Current (A) across Mass-to-Charge ratios (m/e) for CBW biochar and EFB biochar during CO_2 gasification

The mass spectrometry (MS) results indicate that both chicken bone waste (CBW) biochar and empty fruit bunch (EFB) biochar efficiently generate essential syngas—hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4)—during CO_2 gasification. In terms of hydrogen production (m/e = 2, 4), EFB biochar demonstrated significantly higher ion currents (7.85×10^{-9} A and 1.14×10^{-10} A, respectively) in comparison to CBW biochar (6.00×10^{-9} A and 7.21×10^{-11} A). This result can be attributed to the increased volatile matter content of EFB biochar [19] compared to CBW biochar [17]. This characteristic allows for quicker breakdown of hydrocarbons, resulting in accelerated hydrogen release. Conversely, CBW biochar demonstrates a steady, although slow hydrogen release rate, underscoring its capability for sustained syngas generation at a stable but lower output level relative to EFB biochar.

Both biochars exhibited significant ion current peaks for carbonaceous gases, notably CO and CO_2 (m/e = 28, 44). EFB biochar exhibited marginally elevated values (9.28×10^{-6} A for CO and 5.78×10^{-6} A for CO_2) in comparison to CBW biochar (8.59×10^{-6} A for CO and 5.71×10^{-6} A for CO_2). These findings underscore the capacity of both biochars to release carbon-rich gases, which is crucial for efficient syngas production. Both biochars' high fixed carbon content, measured at 55.76% for EFB biochar [13] [7], indicates its effectiveness in generating CO and CO_2 during gasification and serves as an essential precursor for producing syngas components.

Comparable patterns were seen for methane (CH_4) production (m/e = 16, 18). EFB biochar exhibited superior ion currents (9.49×10^{-7} A and 9.74×10^{-7} A) in comparison to CBW biochar (9.91×10^{-7} A and 4.92×10^{-7} A). This suggests that the heightened reactivity of EFB biochar facilitates the release of lighter hydrocarbons, consistent with its elevated thermal breakdown rate.

The comparison analysis highlights unique advantages for each form of biochar. CBW biochar, noted for its exceptional thermal stability and high fixed carbon content, is well suited for extended gasification operations, facilitating consistent syngas generation over lengthy periods. Conversely, EFB biochar, due to its increased reactivity and expedited breakdown, is more suited for quick gasification cycles, yielding more excellent gas production in reduced timeframes.

These results highlight the potential of CBW and EFB biochars as sustainable sources for syngas production. Future studies must concentrate on optimising gasification parameters specific to each biochar type while also investigating the incorporation of biochar-derived syngas into extensive renewable energy systems. These innovations will enhance efficiency, scalability, and sustainability, tackling significant difficulties in waste management and renewable energy generation.

4. Conclusions

This study highlights the possibility of employing biochar from EFB and CBW for CO_2 gasification-based syngas production. The findings indicate that CBW biochar, characterised by elevated fixed carbon concentration and enhanced thermal stability, is more appropriate for extended gasification procedures, guaranteeing reliable and uniform syngas generation. Conversely, EFB biochar, characterised by its high reactivity and swift gas release, is ideal for fast gasification cycles, facilitating faster syngas generation but perhaps limiting sustained output. Techniques such as TGA-MS and FTIR demonstrated substantial structural changes in the biochar during pyrolysis, including increased carbon content and decreased functional groups, which are essential for effective gasification. These findings emphasise the efficacy of CO_2 gasification as a sustainable approach to syngas production, with typical gasification efficiencies of 70-85%, providing a feasible option for waste management and renewable energy generation. Subsequent research should prioritise the expansion of trials, investigate the catalytic impacts of ash content, and integrate biochar-based syngas systems with other renewable energy technologies to enhance overall efficiency and sustainability. This study improves the comprehension of biochar's function in waste-to-energy strategies and offers significant insights for optimising its implementation in renewable energy contexts.

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