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Solar Pyrolysis of Empty Fruit Bunch (EFB): Biochar Characterization and Potential Applications

Alia Syafiqah Abdul Hamed[1], Muhammad Syarifuddin Yahya[1], Nurul Adilah Abdul Latiff[1], Syamsul Ma'arif[2], Nur Farizan Munajat[3,*]

[1] Faculty of Ocean Engineering Technology, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia
[2] Industrial Engineering Department, Faculty of Engineering, Universitas Sarjanawiyata Tamansiswa, Yogyakarta 55167, Indonesia
[3] Renewable Energy and Power Research Interest Group (REPRIG), Eastern Corridor Renewable Energy Special Interest Group (SIG), Faculty of Ocean Engineering Technology, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia

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ABSTRACT

Solar pyrolysis technology offers a sustainable approach to valorise Malaysia's abundant solar energy as well as biomass resources from the palm oil industry. This study focuses on the characterization of biochar produced from solar pyrolysis of empty fruit bunches (EFB) using a Fresnel lens as a solar concentrator. Characterization of the biochar was conducted using thermogravimetric analysis (TGA), X-ray diffraction (XRD), and scanning electron microscopy (SEM). TGA results showed that biochar exhibited enhanced thermal stability, retaining 47.8 % of its mass at 500 °C compared to only 11.9 % for raw EFB, due to the removal of volatile content during pyrolysis. XRD analysis revealed a transformation from crystalline cellulose in raw EFB, to amorphous carbon in biochar. SEM imaging demonstrated a porous morphology and a reduction in median particle size from 9.928 ± 4.571 µm in raw EFB to 8.000 ± 3.683 µm in biochar, suggesting an increased surface area and enhanced functional properties. These findings highlight the potential of solar pyrolysis for producing biochar with improved thermal, structural, and functional characteristics, suitable for applications such as soil amendment, adsorption, and energy storage. This research emphasizes the importance of material characterization in optimizing biochar properties and advancing renewable energy technologies for sustainable development.

Keywords:
Solar pyrolysis; oil palm biomass; solar energy; renewable energy; biochar; energy recovery

1. Introduction

The global demand for palm oil, encouraged by its use in food, cosmetics and biofuels, makes Malaysia a key player, contributing 26% of production and 34 % of exports globally [1]. As of 2023, the Malaysian oil palm industry showed growth compared to 2022, with crude palm oil production rising by 0.5 % (from 18.45 to 18.55 million metric tonnes) and oil extraction efficiency improving from 19.70 to 19.86 % [2]. This growth was supported by improved labour availability, higher fresh fruit bunch yields and enhanced processing efficiency, with the oil extraction rate rising to 19.86 %.

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[*] *Corresponding author.*
E-mail address: nurfarizan@umt.edu.my

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These advancements contributed to increased biomass production, providing additional opportunities for renewable energy and bio-based product development [3,4].

The abundance of empty fruit bunches (EFB), a residual byproduct of palm oil production, estimated at over 21.3 million tons annually in Malaysia, presents both an environmental challenge and an opportunity [5]. Converting this biomass into value-added products through pyrolysis offers a sustainable pathway for waste valorisation, offering a significant feedstock for biochar production [6-8]. Pyrolysis, a thermochemical conversion process, breaks down organic matter in an oxygen-limited condition, producing biochar, bio-oil and syngas. This technology has garnered attention for its capability to convert biomass waste into useful products, with biochar standing out for its potential applications in agriculture, energy storage and environmental remediation [9]. Solar pyrolysis, an advanced variant of conventional pyrolysis, introduces significant environmental and economic advantages by utilizing renewable solar energy as the heat source. This approach minimizes greenhouse gas emissions and operational costs while maintaining high thermal efficiency.

Compared to conventional methods, solar pyrolysis achieves higher sustainability and aligns with the global transition to renewable energy technologies. Recent advancements in solar-enhanced pyrolysis have demonstrated its effectiveness in producing high-quality biochar from various biomass sources. Aspiazu-Méndez *et al.,* [10] achieved optimized biochar properties from pecan shells by analysing thermal profiles, revealing improvements in lignin degradation and moisture evaporation. Lobato-Peralta *et al.,* [11] demonstrated that solar pyrolysis of agave bagasse produced biochar with enhanced porosity and capacitance, ideal for energy storage applications. Similarly, Li *et al.,* [12] introduced Solar Char-Cycling Pyrolysis (SCCP), achieving superior energy and exergy efficiencies (90.81 and 76.51%) while utilizing biochar as a heat absorber, addressing challenges like solar window contamination and boosting energy utilization. These studies showcase solar pyrolysis as a sustainable and efficient method for producing biochar with enhanced properties for diverse applications. EFB, with its high lignocellulosic content and low ash, emerges as an ideal feedstock for this solar pyrolysis technology.

Literature studies emphasize the unique physicochemical properties of EFB-derived biochar, such as high carbon content, surface area and porosity, which make it suitable for various applications in soil amendment, water purification and carbon sequestration [13]. Lee *et al.,* [14] investigated the characterization of EFB biochar by a high specific surface area and porosity, exhibits excellent adsorption properties, making it effective in removing pollutants such as nitrogen oxides and volatile organic compounds (VOCs). Azni *et al.*, [15] found that EFB biochar produced via microwave-assisted pyrolysis had a high heating value (6,317.99 kcal/kg) comparable to sub-bituminous coal, with significantly lower CO and NOx emissions, demonstrating its potential as a cleaner solid fuel. Additionally, Bakhtiar *et al.,* [16] highlighted that low to medium pyrolysis temperatures produced biochar rich in oxygen-containing functional groups, while higher temperatures enhanced its BET surface area, microporosity and aromaticity, making it ideal for pollutant adsorption and energy storage applications. These properties highlight its potential in environmental applications, from pollutant adsorption to improving soil fertility and pH for enhanced crop yield.

Hence, the pyrolysis process produces biochar with distinct properties that make it highly versatile for applications. The novelty of this research lies in its emphasis on leveraging solar pyrolysis technology to optimize the production and characterization of EFB-derived biochar. By incorporating solar renewable energy into the pyrolysis process, this research focuses on a crucial gap in biomass valorisation while advancing scientific knowledge in the field. The objectives of this research are to investigate the physicochemical and thermal properties of biochar produced via solar pyrolysis, assess its potential applications and provide a scientific basis for scaling this technology to industrial levels.

2. Methodology

2.1 Sample Preparation and Biochar Production from Solar Pyrolysis

This research was conducted at Universiti Malaysia Terengganu utilizing EFB feedstock sourced from TDM Sungai Tong Palm Oil Mill in Terengganu. Before the experiments, the EFB was dried, ground and sieved to achieve a particle size of less than 3 mm. Each trial employed a 0.3 g sample of the processed material. The properties of the EFB used in this research are detailed in Table 1. Proximate analysis was performed following the JIS standard (M8812), while the elemental composition was determined using a CHNS analyser.

Table 1
The proximate and ultimate analysis of EFB

Proximate analysis (wt.%)		Ultimate analysis (wt. %)	
Moisture content (MC)	7.794	Carbon content (C)	45.590
Ash Content (AC)	5.227	Hydrogen content (H)	5.565
Volatile Matter (VM)	71.200	Nitrogen content (N)	1.503
Fixed Carbon (FC)	15.779	Sulphur content (S)	0.100
		Oxygen content (O)	47.241

Figure 1 depicts a schematic diagram illustrating the solar-driven pyrolysis of EFB, refined based on insights from a previous preliminary study [17]. A Fresnel lens measuring 30 cm by 40 cm, with a focal distance of 30 cm, was used to concentrate sunlight into a 1 cm diameter spot. During the experiment, the reactor was positioned at the lens's focal point and an inert atmosphere was maintained by purging argon gas at a flow rate of 10 ml/min. Solar irradiance and ambient temperature were recorded using a Seaward 200R irradiance meter, a device known for delivering accurate data for measuring solar irradiance [18]. A Type K thermocouple is positioned at the focal point inside the reactor to monitor the internal temperature. The EFB feedstock underwent pyrolysis in the reactor for a duration of 20 minutes per trial.

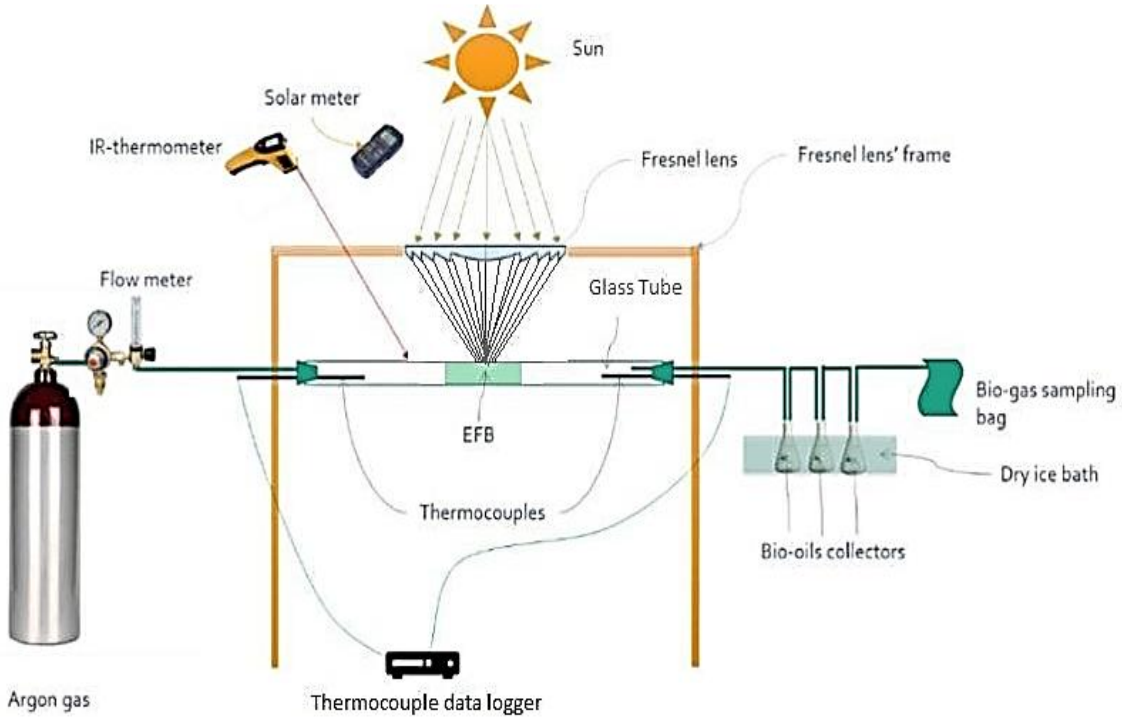


Fig. 1. Schematic diagram of solar-driven pyrolysis

The solid biochar yield obtained after pyrolysis was weighed and its percentage was determined using Eq. (1).

Biochar Yield (wt. %) = (mass of char) / (mass of feedstock) × 100% (1)

The data reported in this study were obtained from at least three independent experiments conducted under the same solar irradiance and internal reactor temperature conditions. To validate the results, a comparative analysis was performed by referencing previous studies on conventional pyrolysis of EFB. This comparison provided insights into how solar-driven pyrolysis influences biochar characteristics relative to conventional methods.

2.2 Characterization of Biochar

To characterize the biochar obtained from the solar pyrolysis process, a combination of thermogravimetric analysis (TGA), X-ray diffraction (XRD) and scanning electron microscopy (SEM) was employed. Thermal degradation of the biochar was analysed using a TGA analyser (TGA/SDTA851e, Mettler Toledo, USA) across a temperature range of 30 to 800 °C in 10 °C/min under a 100 mL/min nitrogen gas flow. This allowed for the measurement of the biochar's thermal stability and decomposition profile. XRD analysis was conducted using a high-resolution Rigaku D/teX Ultra 250 to examine the crystalline phases and structural properties of the biochar. The morphological characteristics of the biochar were analysed using a scanning electron microscope (SEM; JEOL JSM-6360LA). Prior to imaging, the biochar samples were mounted on carbon tape and coated with a thin layer of gold using an Auto Fine Coater (JFC 1600) under vacuum conditions. This ensured optimal conductivity and image clarity. The SEM images were captured at approximately ×1,500 magnification to observe the surface structure and porosity of the biochar.

To strengthen the validation, the properties of the biochar produced from solar pyrolysis were compared with data from cited studies on conventional pyrolysis of EFB. This approach enabled a broader understanding of the advantages and potential trade-offs of using solar-driven pyrolysis relative to traditional thermal conversion methods.

3. Results and Discussions

3.1 Characterization of Biochar

The biochar produced through solar pyrolysis exhibited varying yields depending on the temperature profiles and levels of solar irradiance applied during the process. The optimum biochar yield, 31.48 %, was achieved under an average solar irradiance of 957 $\pm$ 29 W/m² and an average temperature of 435 $\pm$ 43 °C. Comparatively, conventional pyrolysis on EFB biochar reports similar yield ranges of 30-50 % at lower pyrolysis temperatures (300 – 500 °C), with yields declining significantly at higher temperatures (≥ 600 °C) due to devolatilization and carbon burn-off. Bakhtiar *et al.,* [19] reported that KOH-activated EFB biochar produced at 400–600 °C achieved yields ranging between 30–40 %, similar to the optimum biochar yield observed in this solar pyrolysis study, while also exhibiting well-developed porosity that enhances its functional properties.

Similarly, Nalaya *et al.,* [26] reported that biochar yield at 350°C (37.3 ± 0.7 %) and 550 °C (27.7 ± 0.3 %) in the study indicate a decreasing trend with increasing pyrolysis temperature, which is consistent with the solar pyrolysis trend where moderate temperatures help retain higher biochar yields. Thus, the yield obtained from solar pyrolysis falls within the range of biochar yields from conventional pyrolysis at moderate temperatures (300 – 500 °C). This highlights the influence of controlled solar irradiance and temperature optimization on the pyrolysis process efficiency. The EFB feedstock and this resulting biochar were characterized using TGA, XRD and SEM analysis. Statistical analysis was incorporated to assess the reproducibility of the experimental results, with standard deviations provided where applicable.

3.1.1 Thermogravimetric analysis

TGA analysis shown in Figure 2 provides a detailed insight into the thermal decomposition behaviour of EFB raw and its biochar. The TGA curve typically exhibits three main stages: the first is dehydration, followed by devolatilization, which results in biochar formation and finally, the gradual conversion of the biochar into a more carbon-rich substance [20]. The first stage of decomposition occurs below 200 °C, resulting in minimal mass loss, primarily because of the evaporation of water and light volatile compounds.

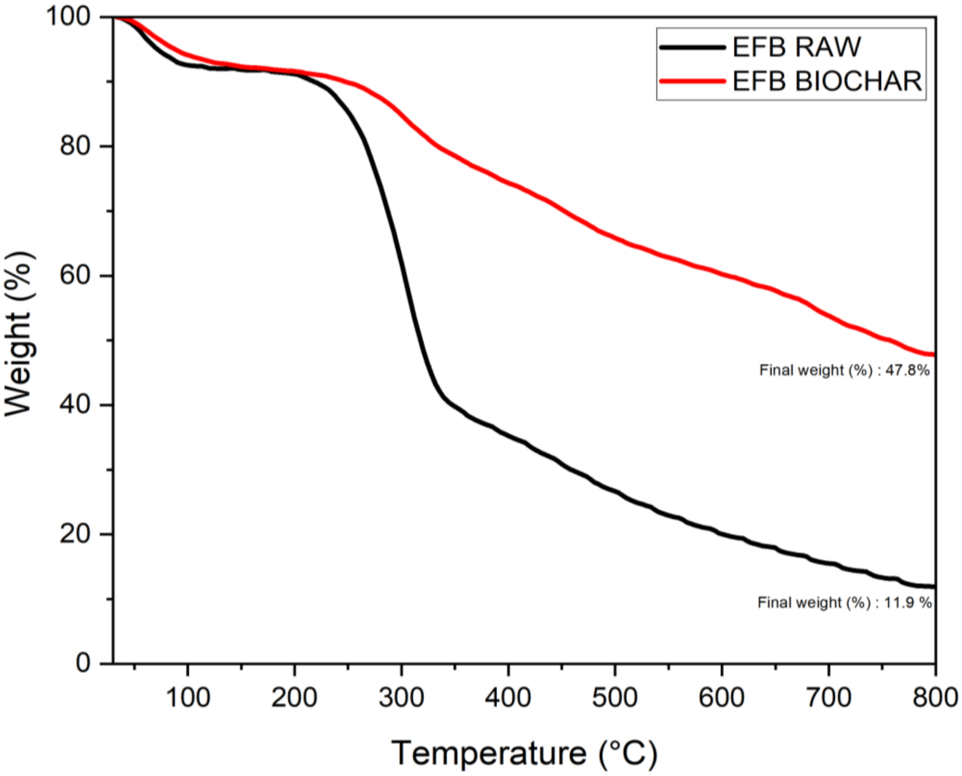


Fig. 2. TGA analysis result for EFB raw and biochar

The initial weight loss below 200 °C accounts for about 10 %, caused primarily by the release of moisture and light volatiles. Both EFB raw and biochar show minimal weight loss due to moisture evaporation, with raw EFB dropping slightly more steeply from 100 % to 91.2 %, whereas biochar retains more mass (91.6 % at 200 °C). As the temperature increases to 300 °C, raw EFB undergoes significant weight loss (down to 61.7 %), primarily attributed to the decomposition of hemicellulose and cellulose, while biochar retains 84.3 % of its weight, indicating reduced volatile content due to the pyrolysis process. Between 300 and 500 °C, the devolatilization phase is prominent for raw EFB, with its weight plummeting further to 26.5 %, showcasing the instability of unprocessed biomass at higher temperatures. Conversely, biochar maintains its structure better, retaining 65.7 % of its weight at 500 °C.

In the final stage beyond 500 to 800 °C, raw EFB finally stabilizes at 11.9 %, representing the residual ash content in this inert atmosphere process. These results closely align with those obtained from the raw EFB used in the study by Chala *et al.,* [21], showing a final weight retention of 11.1% Biochar shows superior thermal stability, with a percentage of 47.8 %, signifying its suitability for high-temperature applications. In comparison, the conventional pyrolysis biochar of EFB at a pyrolysis temperature of 550 °C by Azman *et al.,* [22] retains approximately 40% of its final weight. This trend further highlights the enhanced thermal stability of biochar produced via solar pyrolysis, attributed to greater volatile elimination and an increase in carbon-rich fractions. As depicted in Figure 2, solar pyrolysis effectively transforms EFB into a more thermally stable material with reduced volatile content, making biochar a versatile product for sustainable applications.

3.1.2 Xray diffraction analysis

Figure 3 shows the XRD analysis results of EFB raw and its biochar, highlighting structural transformations due to solar pyrolysis. XRD analysis quantifies crystalline and amorphous regions, which is essential for understanding the material's properties and potential applications. In the raw EFB sample, the dominant diffraction 2θ peak at 21.82° corresponds to the crystalline cellulose phase (cellulose I), which is a characteristic feature of lignocellulosic biomass. Additional smaller 2θ peaks at 9.81°, 31.93° and 49.86° indicate minor crystalline components, likely related to hemicellulose or other organic compounds. This raw EFB peak range 2θ similar to the studies by Sukiran *et al.,* [23] and Soha *et al*., [24].

In contrast, the XRD pattern of EFB biochar shows significant structural changes. The major 2θ peak at 28.25° suggests the formation of carbonaceous, amorphous structures due to the breakdown of cellulose and hemicellulose during pyrolysis. Additional 2θ peaks at 20.79°, 40.42° and 50.09° indicate residual crystalline phases, likely from mineral impurities or restructured carbon. These findings align with those of Laili *et al.,* [25], who reported a similar highest peak of 28.0 ° in EFB biochar produced from conventional pyrolysis at ~450 °C. The findings highlight the transformation of the EFB from a lignocellulosic material with crystalline cellulose to a predominantly amorphous carbon-rich biochar. The sharper and more distinct peaks in biochar suggest increased thermal stability and graphitization during pyrolysis. The reduced crystallinity in biochar compared to raw EFB makes it more suitable for applications such as adsorbents, construction material, soil amendment or as a fuel source due to its enhanced carbon content and porous structure.

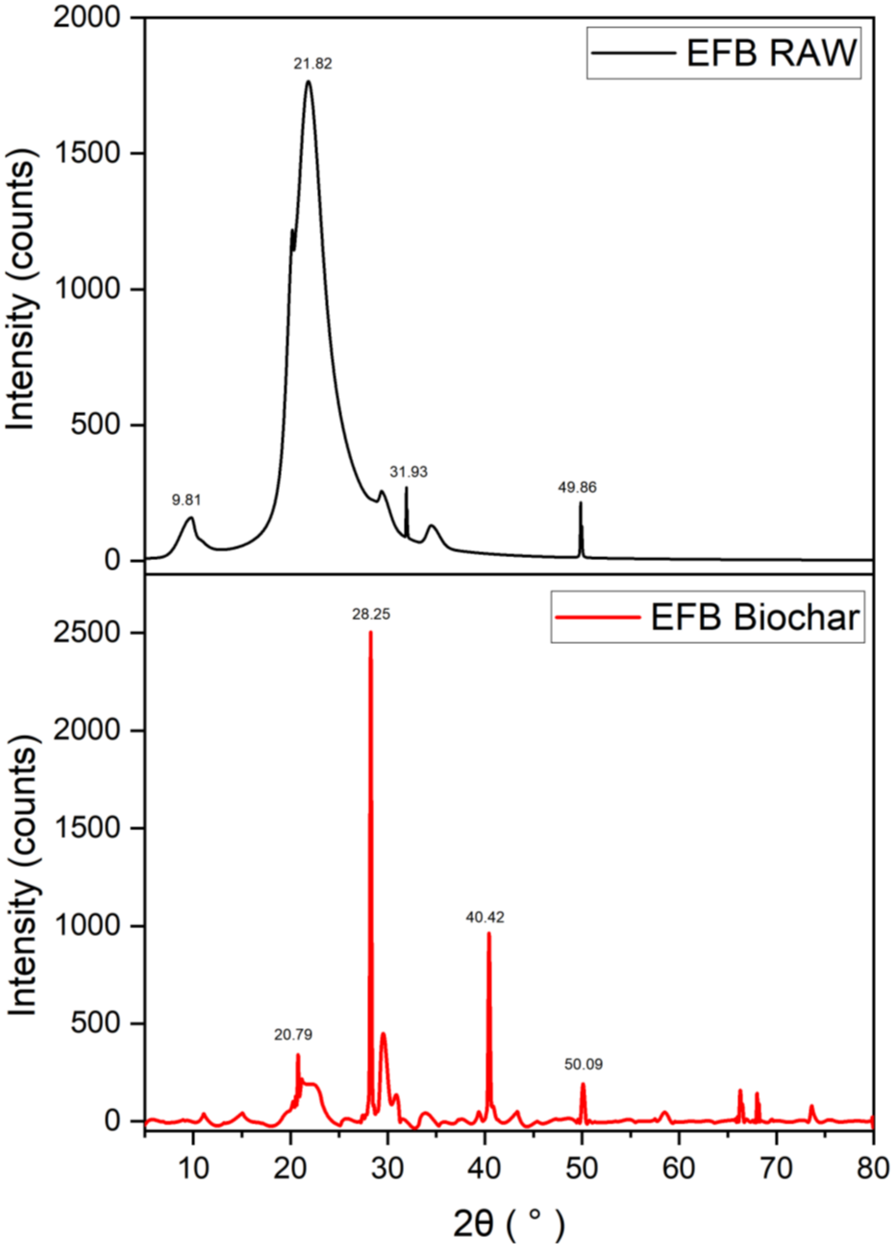


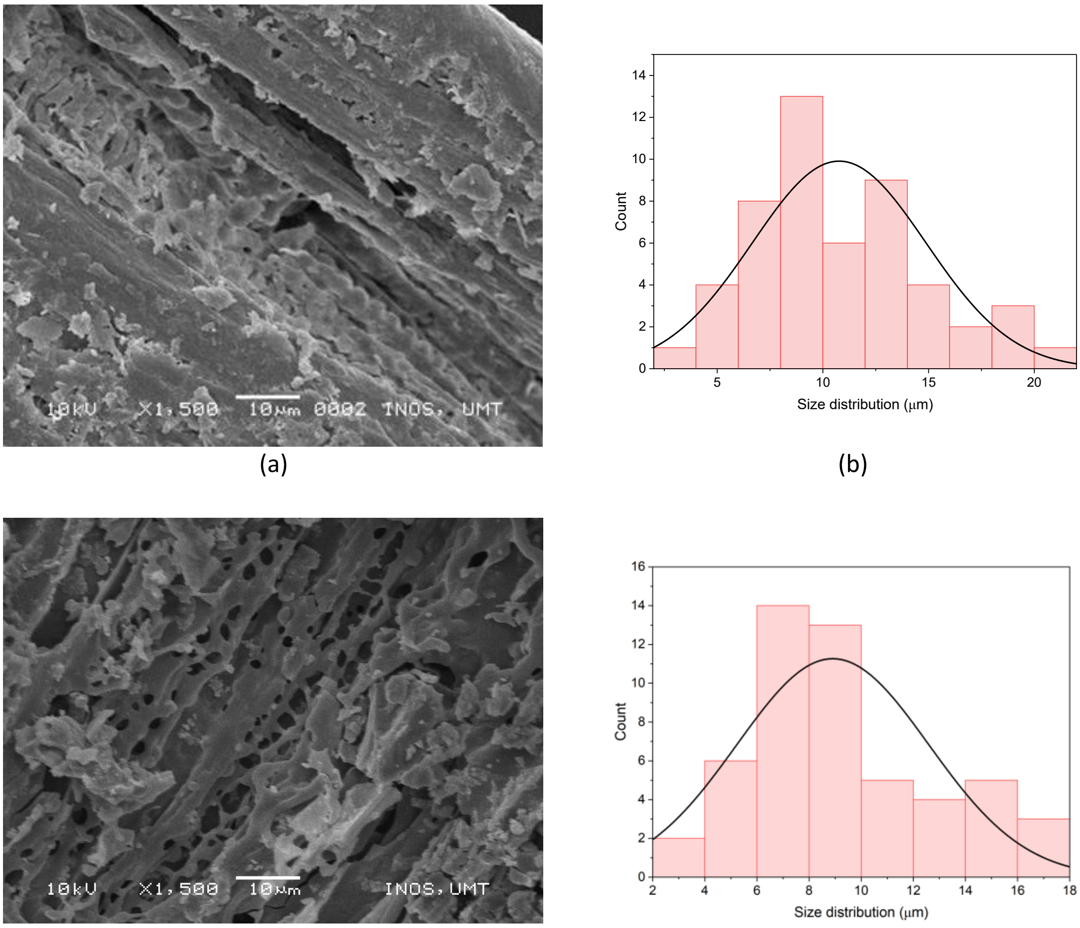
Fig. 3. XRD characterization results for EFB raw and biochar

3.1.3 Scanning electron microscopy analysis

Figure 4 provides SEM images and particle distribution size analysis for both EFB raw and biochar. Raw EFB (Figure 4(a)) exhibits a fibrous and intact structure, indicative of its lignocellulosic composition. In contrast, after pyrolysis, the biochar (Figure 4(c)) displays a porous structure with noticeable degradation, resulting from the breakdown of cellulose and hemicellulose during the pyrolysis process. These structural changes align with findings from Bakhtiar *et al.,* [19], who reported that EFB biochar produced at 400–600°C exhibited significant porosity development, while biochar from higher pyrolysis temperatures (>800°C) exhibited excessive carbonization, leading to reduced biochar yield and increased micropore formation.

The particle size distributions, represented in histograms (Figure 4(b) and Figure 4(d)), show a slight reduction in median particle size from 9.928 ± 4.571 µm for raw EFB to 8.000 ± 3.683 µm for EFB biochar. This decrease is attributed to rapid devolatilization and fragmentation of biomass components under high heat flux conditions. This decrease aligns with studies by Soha *et al.,* [24], which reported similar trends in particle size reduction due to thermal decomposition and structural fragmentation during pyrolysis. Similarly, Nalaya *et al.,* [26] who observed that EFB biochar pyrolyzed at 350°C retained larger particles (from 10 to 15 µm), while biochar produced at 550–650°C exhibited finer structures (6–10 µm) due to progressive thermal breakdown. The narrower size distribution in biochar reflects the homogenization effect of thermal treatment.

The reduced particle size and enhanced porosity in biochar improve its functional properties, such as adsorption capacity and reactivity in thermal and catalytic applications. This combination of physical and structural transformations underscores the suitability of EFB biochar for various industrial and environmental uses, such as energy production, pollutant remediation and soil enhancement. The findings further confirm that the pyrolysis process not only transforms the chemical composition but also optimizes the physical properties of the material for value-added applications.



(a) (b)

(c) (d)

Fig. 4. SEM image and particle distribution size for EFB (a-b) raw and (c-d) biochar at 1500x magnification

4. Conclusion

This study demonstrates the efficacy of solar pyrolysis in converting EFB, a by-product of the palm oil industry, into high-quality biochar. The characterization results demonstrate the significant impact of solar irradiance and temperature optimization on the pyrolysis process and the resulting biochar properties. TGA analysis revealed the enhanced thermal stability of the biochar, retaining 47.8 % of its weight at 800 °C compared to 11.9 % for raw EFB. XRD analysis confirmed the transformation of EFB from crystalline cellulose (peak at 2θ=21.82°) to amorphous carbon-rich biochar (peak at 2θ=28.25°), enhancing its structural and thermal properties. SEM revealed a porous structure and a reduced median particle size of 8.000 ± 3.683 µm in biochar, compared to 9.928 ± 4.571 µm in raw EFB. These changes indicate an increase in surface area and functional capabilities, which is crucial for applications such as soil amendment, construction material and energy storage. This research supports the advancement of renewable energy technologies and contributes to Malaysia's environmental sustainability and resource management goals. Further studies should focus on optimizing reactor design and process parameters for industrial applications, as well as evaluating the long-term performance of biochar in specific applications.

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