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Letter

# Synergetic Torrefaction of Oil Palm Fronds Using Heat Generated from Combustion with Burner

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## Abstract

Biomass offers a renewable pathway to sustainable energy, with Malaysia's oil palm industry producing significant biomass residues such as oil palm fronds (OPFs). However, the high moisture content and low energy density of OPFs restrict their direct application as biofuels. This study investigates the torrefaction of OPFs using a custom-designed reactor heated by liquefied petroleum gas (LPG), as a surrogate for syngas combustion. Key factors such as heat loss control, temperature uniformity, and reactor calibration were emphasized to ensure reliable, reproducible experimental conditions. The results demonstrate that torrefaction improved the energy density and moisture resistance of OPFs, highlighting the effectiveness of LPG-based heating systems. This research provides a model for future syngas applications, with controlled conditions enabling consistent thermal treatment. The findings suggest that syngas-derived heat can efficiently support OPF torrefaction, advancing sustainable biomass energy technologies and improving the economic viability of biomass utilization at an industrial scale.

**Categories:** Combustion and Alternative Fuels, Energy Efficiency and Conservation, Environmental Engineering and Sustainability
**Keywords:** oil palm fronds, torrefaction, lpg combustion, syngas surrogate, calorific value, biomass energy

## Introduction

Biomass, as a renewable energy source, plays a vital role in promoting sustainability. In Malaysia, biomass from the oil palm industry presents a promising alternative for both renewable energy and raw material production. As one of the largest producers and exporters of oil palm, Malaysia contributes approximately 26% to the global supply [1]. Oil palm fronds (OPFs), in particular, hold significant potential as biofuels due to their high volatile matter content. However, biomass materials, including OPFs, typically exhibit low energy density and high moisture content (MC), ranging from 30 to 60 wt% [2]. This is because pruned fronds are often left on the ground and exposed to rainwater, which increases MC. The high MC reduces energy density, thereby decreasing the efficiency of energy conversion processes [3]. Although drying can lower MC, it does not prevent subsequent moisture reabsorption.

Thermal pre-treatment of biomass, carried out at moderate temperatures (200-300°C) under atmospheric conditions and in an oxygen-free environment, plays a vital role in processing organic by-products for energy applications. This method has been widely recommended to improve the quality of solid biofuels by eliminating moisture, reducing moisture absorption tendencies, and enhancing ease of grinding [4]. Torrefaction, in particular, presents an effective solution to these challenges. Studies have highlighted torrefaction as an efficient biomass pre-treatment [5]. It enhances biomass properties by increasing energy density, reducing MC, and improving hydrophobicity. Torrefied biomass retains about 70% of its original mass while conserving up to 90% of its original energy content [6], thereby significantly improving energy density and reducing biomass handling and transportation costs. Additionally, torrefied biomass exhibits superior grindability, increasing pulverizing mill output by 3-10 times compared to raw biomass.

Torrefaction is influenced by several factors, with the most significant being the lignocellulosic composition of the biomass, the temperature, and the residence or holding time. Various studies have explored the torrefaction of OPFs [7]. For instance, Matali [8] examined the torrefaction of OPFs and Leucaena leucocephala pellets, finding significant improvements in calorific value and hydrophobicity, making them more suitable for energy production and long-term storage. Similarly, Lau et al. [9] investigated different torrefaction conditions to optimize the properties of oil palm biomass, demonstrating the potential of torrefied OPFs for high-efficiency energy conversion. Temperature plays a critical role in governing the torrefaction process and the resulting properties of the biomass. Thaim et al. [10] found that the higher heating value (HHV) increased with increasing torrefaction temperature, while mass and energy yield decreased.

Torrefaction can be conducted using an integrated system that utilizes heat generated from combustion processes, including direct heating from a burner. Utilizing syngas combustion for torrefaction has the

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potential to reduce the energy consumption of the process. However, the use of syngas-derived heat for torrefying OPFs is not yet a common practice. While syngas and liquefied petroleum gas (LPG) differ in composition, both are gaseous fuels, allowing LPG to serve as a practical surrogate in controlled experiments simulating syngas combustion behavior.

In addition to traditional torrefaction, alternative technologies have been explored to enhance biomass conversion. Microwave-assisted torrefaction (MAT) has been identified as a promising alternative due to its ability to rapidly heat biomass, leading to shorter processing times and reduced energy consumption. MAT has been shown to enhance mass yield, energy yield, and HHV, as reviewed by Potnuri et al. [11]. Andersone et al. [12] demonstrated that microwave heating increases the higher heating value of biomass, although energy yield decreases with rising temperature. The extent of these losses is influenced by the biomass structure, chemical composition, and the degree of lignocellulosic decay [12]. The selective and efficient nature of microwave heating can also improve the uniformity of thermal treatment, enhancing the overall effectiveness of the torrefaction process. Moreover, Aziz et al. [5] highlighted the increased grindability and reduced MC achieved by microwave-assisted torrefaction, which enhances biomass properties for efficient combustion and energy production. However, achieving uniform microwave energy distribution remains a major challenge, particularly when large quantities of biomass are placed within a spacious microwave cavity. This often leads to uneven heating and the formation of localized hot spots, a phenomenon widely reported in studies on microwave-assisted heating processes [11]. Future research will focus on scaling up microwave reactors for biofuel production.

Another emerging technology is the use of electric furnace torrefaction. Electric furnaces provide precise control over temperature and heating rates, ensuring uniform and stable treatment of biomass. Some studies have employed this method to torrefy biomass, including vertical reactors [13] and vertical tubular stainless steel reactors [10]. These studies investigated the electric furnace torrefaction of various biomass materials, including OPFs, and reported improvements in energy density and hydrophobicity similar to those achieved by conventional torrefaction methods. However, the higher energy consumption, especially at industrial scales, remains a challenge. Despite this limitation, electric furnace torrefaction is still widely used in laboratory-scale experiments to study the thermal decomposition and combustion properties of biomass.

Achieving efficient and consistent torrefaction requires minimizing heat loss, maintaining uniform reactor temperatures, and ensuring accurate reactor calibration. Proper heat management minimizes energy waste and maintains stable process conditions, which are critical for reliable torrefaction. Uniform temperature distribution inside the reactor ensures that all biomass particles are subjected to consistent thermal treatment, preventing issues like partial torrefaction or over-carbonization. Accurate calibration of temperature sensors and control systems further guarantees the reliability, accuracy, and repeatability of experimental results. In the context of using LPG as a surrogate for syngas, precise control over heating conditions becomes even more important to replicate the expected performance of future syngas-based systems. Addressing these factors is essential to optimize the torrefaction process, enhance energy conversion efficiency, and validate the system’s potential for industrial-scale applications.

The principal objective of this study is to investigate the torrefaction performance of OPFs using a custom-designed reactor heated by LPG combustion, with the aim of simulating future applications involving syngas. This research seeks to optimize the heating process for maximum energy conversion efficiency and to evaluate the feasibility and potential of using syngas-based torrefaction systems for sustainable and efficient industrial applications.

# Materials And Methods

## Biomass preparation

Fresh OPFs were collected from a local oil palm plantation in Malaysia (specific location undisclosed) as a biomass feedstock that is readily available, as they are not utilized for industrial processing. They were processed by removing leaflets and segmenting the petiole into tip, middle, and base and further cut to uniform dimensions (5-8 mm width, 30-40 mm length) to facilitate uniform processing. Figure *1* shows samples of the frond cuts. The raw OPFs were analyzed, focusing on key characteristics such as MC and calorific value.


**FIGURE 1: Samples of the frond cuts**

## Reactor design and heat management

The torrefaction process relies on heat generated from the combustion of LPG. To ensure consistent results, a torrefaction reactor is designed to replicate the conditions studied in prior research on torrefaction properties. This stage requires a thorough understanding of the torrefaction process. The torrefier must be carefully designed to ensure uniform heating of the OPFs during torrefaction. Following the design phase, the torrefier is fabricated according to specifications.

The torrefaction reactor is designed in this study with considerations on uniform heat distribution, temperature control, and rate of heat transfer. Shown in Figure 2 is the reactor, which uses a modified gas cylinder. The torrefaction reactor features a stainless-steel biomass chamber housed within a modified gas cylinder. The system includes a perforated internal pipe burner for even flame distribution, a controllable gas valve, and a sliding zinc plate to limit oxygen ingress. The chamber was thermally insulated using ceramic fiber blankets to minimize heat loss, and ambient conditions were monitored during trials.

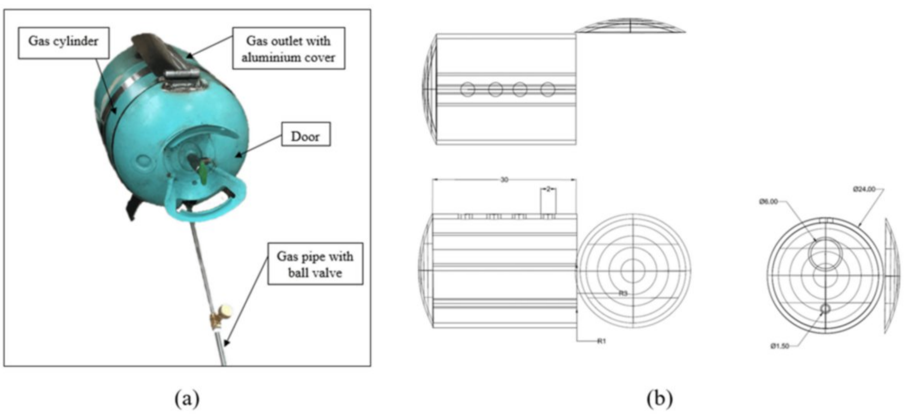


**FIGURE 2: The torrefaction reactor (a) photograph (b) detailed drawing**

## Experimental procedure

Before conducting the experiment, key variables such as torrefaction temperature and duration were established. OPFs were torrefied at 200°C, 250°C, and 300°C for durations ranging from 10 to 50 minutes in 10-minute increments. The feedstock was weighed using a precision balance (±0.01 g accuracy) and placed into the reactor. Nitrogen gas was supplied at a flow rate of 30 mL/min (±1 mL/min precision). The sample was heated to the desired temperature at a rate of 10°C/min (±0.5°C/min precision). Once the target temperature was reached, the reaction was allowed to proceed for 10 minutes. Afterward, the biomass was cooled to room temperature, and the torrefied biomass was then retrieved and weighed. Each condition was tested in triplicate. MC, mass yield, and calorific value were measured for both raw and torrefied samples.

## Temperature monitoring and calibration

Three thermocouples (±0.1°C accuracy) were placed along the reactor chamber (top, middle, bottom) to ensure uniform heating. Thermocouples were calibrated against a certified reference thermometer before and after each experiment series. Recorded temperatures maintained a deviation within ±5°C.

## Moisture content determination

The MC of OPFs was determined using the oven method. Samples were placed in an oven at 105°C for 24 hours to ensure complete moisture removal. The weight of each sample was measured before and after drying using a precision weighing balance with an accuracy of ±0.01 g. The same process was repeated for torrefied OPF samples.

## Mass yield determination

Mass yield was calculated from pre- and post-torrefaction weights using

CV (MJ/kg) = -1.3675 + 0.3137 * C + 0.7009 * H + 0.0318 * O

where M represents mass yield.

## Calorific value determination

The properties of the OPFs that were tested include the calorific value and percentage of moisture of OPFs. The calorific value of torrefied and untorrefied OPFs was calculated using an equation developed by Sheng and Azevedo [14].

Calorific value was measured for both raw and torrefied samples. Calorific value was measured using a LECO AC-350 bomb calorimeter following ASTM D5865-03 [15]. Although this standard is primarily designed for coal and coke, its application to biomass is supported by several studies [4,9,14,16]. It is effective due to its reliable bomb calorimetry method, which ensures accurate and reproducible calorific value measurements under controlled combustion conditions. Five tests were conducted to get the average value of energy contained in the OPFs. These tests were done for both fresh OPFs and torrefied OPFs to measure the change in the calorific value. The calorific value was also estimated using the equation developed by Sheng and Azevedo [14]:

CV (MJ/kg) = -1.3675 + 0.3137 * C + 0.7009 * H + 0.0318 * O

where C, H, and O represent the dry weight percentages of carbon, hydrogen, and oxygen, respectively. This equation, although originally developed for coal, has been applied to biomass in various studies and provides a useful comparative analysis.

# Results

## Visual changes

Torrefaction led to progressive darkening of the OPFs from green to black (Figure *3*). Intense torrefaction results in biomass turning black, resembling carbonized material. However, torrefaction and carbonization are fundamentally different thermal treatment methods [4]. Three samples (200°C, 30 min), (200°C, 40 min), and (250°C, 20 min) were selected for further analysis due to optimal color and minimal brittleness.

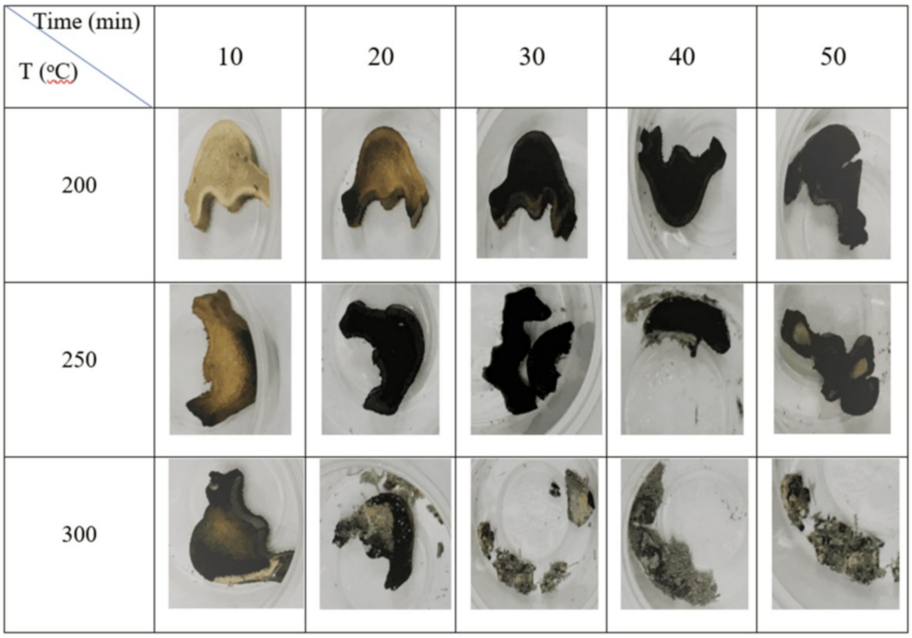


**FIGURE 3: Physical appearance of torrefied fronds at different temperatures and residence times**

## Mass yield

Figure *4* illustrates how yield mass changes with reaction temperature for torrefied fronds at a constant residence time (10 minutes). The data show a clear decreasing trend in yield mass as temperature increases. At lower temperatures, torrefaction has a minimal impact on mass yield, resulting in only slight weight loss. The gradual decrease in mass yield indicates that the torrefaction process has induced minor thermal degradation, likely resulting from moisture loss and slight decomposition of hemicellulose [4]. However, higher temperatures and prolonged durations significantly reduce mass yield due to thermal degradation, with yield loss exceeding 50% at 300°C for extended exposure.

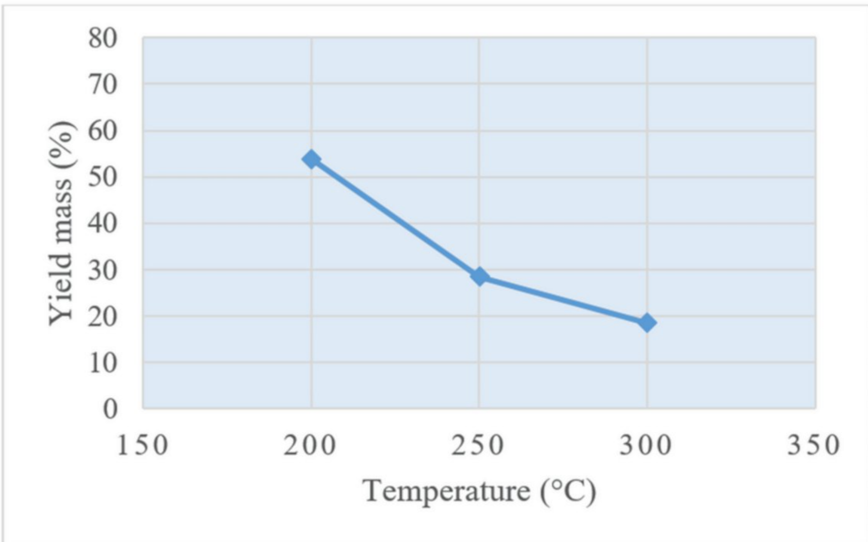


**FIGURE 4: Variation of yield mass with reaction temperature at a constant residence time (10 minutes)**

Figure *5* shows the effect of residence time on yield mass at a constant temperature (250°C). Consistent with the temperature trend, prolonged exposure to heat leads to further decomposition and increased mass loss. Combining high temperatures with long residence times can result in mass losses over 50%, underscoring the substantial impact of these parameters on biomass yield.

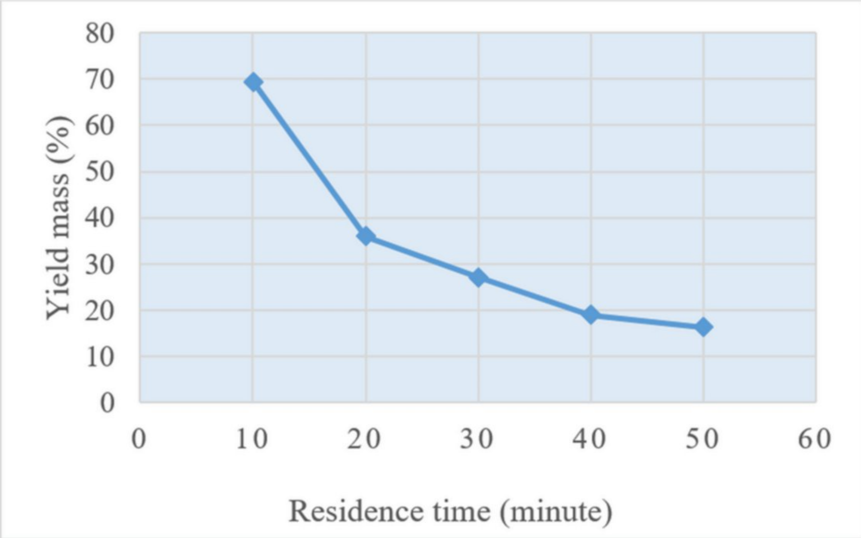


**FIGURE 5: Variation of yield mass with residence time at constant temperature (250°C)**

These findings align with a study by Lau et al. [9], which found that both mass and energy yields decrease with increasing torrefaction temperature. Notably, an optimum temperature of 250°C maintains an energy yield of 92.70% [9].

## Calorific value trends

The calorific value of the biomass increased consistently with both temperature (Figure *6*) and residence time (Figure *7*), reaching a peak of 25.3MJ/kg at 250°C after 20 minutes of treatment. While samples treated at 300°C for the same duration exhibited a higher calorific value, they became too brittle for practical use. These findings align with Rabi and Shaharin [4], who demonstrated that temperature significantly influences calorific value, and Lau et al. [9], who noted that higher temperatures enhance the HHV of torrefied OPFs, achieving a HHV of 26.62 MJ/kg at a torrefaction temperature of 250°C. Both studies highlight the positive correlation between temperature and the energy properties of biomass. This HHV is comparable to that of coal, positioning torrefied OPFs as a promising co-firing fuel for coal power plants.

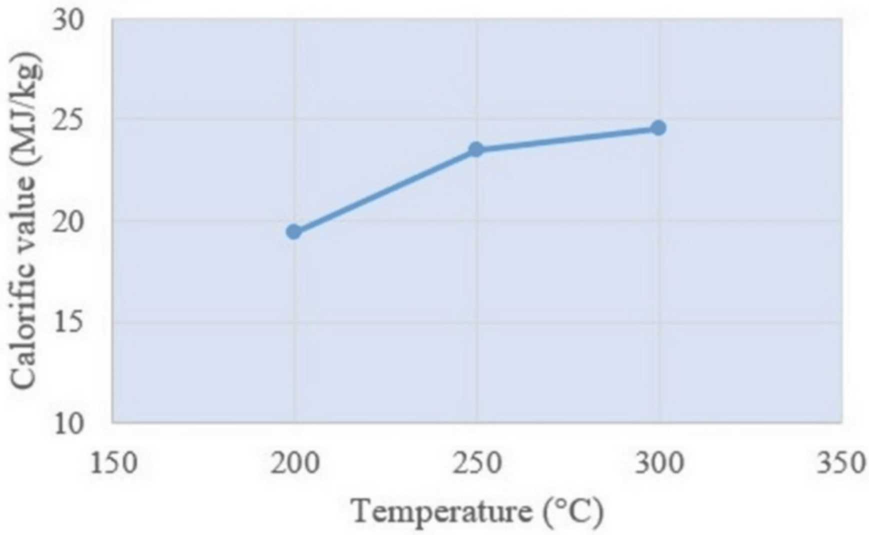


**FIGURE 6: Variation of calorific value with reaction temperature at a constant residence time (20 minutes)**

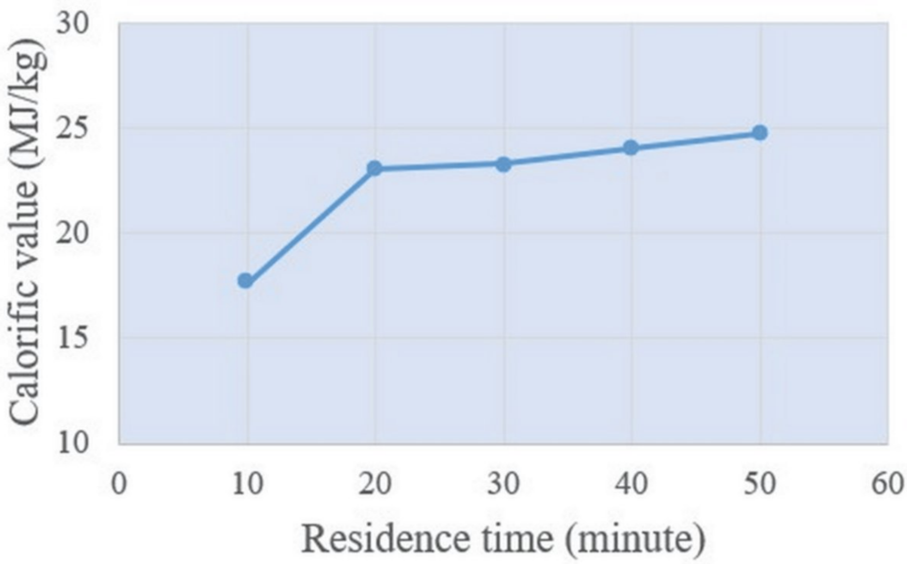


**FIGURE 7: Variation of calorific value with residence time at constant temperature (250°C)**

## Discussion

This study demonstrates the significance of torrefaction in enhancing the calorific value of OPFs. The findings show that reaction temperature and residence time are critical factors influencing the yield mass and energy density of torrefied biomass, consistent with previous research [14,16]. The optimal torrefaction condition of 250°C for 20 minutes emerges as a promising setting, balancing energy density and mass yield while reducing LPG consumption.

### Torrefaction process

The reaction temperature plays a crucial role in determining the physicochemical characteristics of biomass. As the temperature increases, the mass yield decreases, likely due to the thermal degradation of biomass components. This decline is linked to the results of the proximate analysis, which showed a decrease in MC and volatile matter as the temperature increased [14]. While higher reaction temperatures lead to a decrease in mass yield, they notably improve the energy density of the resulting solid products.

### Reactor performance and implications

The custom reactor's effectiveness and efficiency are evident in its ability to produce torrefied biomass with desirable characteristics. The comparison with conventional electric furnace (Lenton Tube furnace) torrefaction demonstrates the potential of this reactor design for industrial applications, achieving a calorific value of 24.56 MJ/kg, surpassing the 21.5 MJ/kg reported in previous studies [16]. The improved calorific values (up to 79% increase) highlight the efficiency of the custom reactor. Torrefaction addresses the limitation of raw biomass's low calorific value, enhancing its energy conversion efficiency. The combination of enhanced energy density and the abundance of OPFs in Malaysia underscores the potential of torrefied OPFs as an effective co-firing fuel with coal.

### Implications for industrial applications

The study's findings have significant implications for the production of high-quality torrefied biomass. The increased calorific value and improved energy density of torrefied OPFs make them a promising feedstock for various industrial applications. However, brittleness at higher settings limits their practical application.

### Future directions

Future research should focus on scaling up the torrefaction process and exploring its potential in various industrial settings. Additionally, further studies could investigate the effects of torrefaction on other biomass feedstocks and explore strategies to mitigate the brittleness of torrefied biomass. Direct syngas combustion trials and a more detailed energy efficiency analysis would also be beneficial.

## Conclusions

This study investigates the torrefaction of OPFs using a custom-designed reactor and demonstrates the feasibility of this process. The results indicate that optimal torrefaction conditions are achieved at 250°C for 20 minutes, resulting in a significant enhancement in calorific value while maintaining structural integrity. The findings highlight the critical role of temperature in influencing the torrefaction process, with residence time having a relatively lesser impact. The enhanced energy density of torrefied OPFs renders them a promising feedstock for industrial applications. Further research is necessary to validate the scalability and syngas compatibility of this process, thereby facilitating its potential adoption in large-scale industrial settings.

## Additional Information

### Disclosures

**Human subjects:** All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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