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Case report

# Development of generating heat energy from empty oil palm bunch powder in cylinder bio-stove with pyrolysis and gasification technology

Paul David Rey [a,*], Mujiyono [b], Didik Nurhadiyanto [b], Helmi Kusuma Perdana [c], Eddy Rusly [d]

[a] *Doctoral Program, Engineering Science, Department of Mechanical Engineering, Universitas Negeri Yogyakarta, Colombo Street No.1, Yogyakarta, 55281, Indonesia*
[b] *Department of Mechanical Engineering, Universitas Negeri Yogyakarta, Colombo Street No.1, Yogyakarta, 55281, Indonesia*
[c] *Department of Mechanical Engineering, National Central University, Taiwan*
[d] *PT. Optimax Prima Teknik, Indonesia*

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ABSTRACT

This research seeks to investigate the potential of generating heat energy from the fine powder of empty fruit bunches (EFB) as a biomass energy source. The fine powder of EFB is compacted into a bio-stove cylinder with three different parts of the moisture content of 9 %, 11 %, and 14 % at the same height. The middle part is then hollowed out like a tube, which becomes a gap for the pyrolysis and gasification processes. The bio-stove has been proven functional and produces stable heat energy to boil 1.5 liters of water with generated heat energy of ±110 Kcal in ±6 min, almost equal to an LPG stove, which is ±180 Kcal in ±6 min [1]. Additionally, it offers a more cost-effective alternative compared to LPG for producing heat energy with prices of IDR 220,000 for EFB stove and IDR 1,260,000 for LPG stove [2] and the pyrolysis and gasification process occurred throughout the entire area of the fine powder of EFB with a moisture content of 9 %, 11 %, and 14 % for 4.5 h with a temperature maximum of 700°C, 836°C and 826°C respectively and thermal conductivity K = 3 W.m/C, K = 0.2 W.m/C and K = 0.8 W.m/C respectively. These findings contribute to the advancement of sustainable heat energy production from EFB biomass as a renewable resource. Furthermore, it offers valuable insight into the combustion behavior of finely ground EFB, including the time required for bio-stoves to sustain a stable flame, which can be used in pyrolysis machine reactors, steam boilers, communal cooking utensils, and other energy applications.

## 1. Introduction

Biomass energy can potentially replace non-renewable energy such as petroleum while offering a more environmentally friendly alternative. Its use can enhance environmental performance, particularly by reducing emissions [3–5]. Various agricultural and plantation biomass sources including palm oil, rubber, wood waste, rice, and coconut residues have been widely utilized for biomass energy production as a renewable energy source [5–7]. As of 2019, Indonesia was the largest palm oil producer in the world, with a land area of 15.08 million hectares and a CPO production of 46.88 million tons. With this area, biomass will be produced in the form of replanted stems, fronds, oil palm empty fruit bunches (EFB), shells, and fruit Fiber. Oil palm solid waste can be used as alternative energy sources [7]. The waste has traditionally been used for compost, animal feed, and industrial fuel directly burned. However, it can also be processed into renewable energy sources such as bio-oil (a substitute for gasoline and diesel), bio-pellets, and bio-briquettes (alternative fuels to gas) [8,9]. One technology for processing oil palm solid waste is to use pyrolysis technology. Pyrolysis is the rapid thermal decomposition of organic compounds (with a residence time of 1 second) at a temperature of 400-600°C in the absence of oxygen to produce liquid, gas, and charcoal [10–12]. Apart from that, oil palm EFB, as a solid waste material for the oil palm industry, can be converted into solid, liquid, and gas products through pyrolysis. Pyrolysis and gasification are two thermochemical processes that can be used to convert oil palm empty fruit bunches into valuable products [13].

In addition, the use of fine powder of oil palm EFB as the main ingredient in the pyrolysis and gasification processes to produce biomass energy plays an important role in achieving the Sustainable Development Goals (SDGs) by contributing to various dimensions of sustainable development, including economic, social, and environmental aspects. Specifically, it supports SDG goals such as affordable and clean energy (Goal 7), food security, ecosystem protection, and responsible consumption and production. Additionally, biomass energy can reduce

* Corresponding author.
*E-mail addresses:* ir0037ft.2023@student.uny.ac.id (P.D. Rey), ir0037ft.2023@student.uny.ac.id (H.K. Perdana).

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fossil fuel dependence, enhance resource efficiency, and promote the development of sustainable and resilient infrastructure. However, it is significant to ensure that biomass production and consumption are managed and regulated appropriately to avoid exacerbating environmental challenges and hindering social development [4,14,15].

Beyond sustainability considerations, an economic analysis has been conducted on the potential of palm oil empty fruit bunch as an alternative fuel to reduce cost of the government's 3 kg LPG subsidy and show the result that EFB Pellet cost IDR 2000 per kg while LPG cost IDR 7000 per kg, highlighting its economic feasibility as a cost-effective energy source [2].

The process of pyrolysis and gasification technologies in different types of reactors and their integration with biomass stoves have explicitly been designed for household or small-scale use, as well as stove design and efficiency are able to handle the specific characteristics of palm biomass [16]. Therefore, it is necessary to conduct a comprehensive study on the optimal conditions (temperature, pressure, feed flow rate) to maximize the efficiency and desired product yield from oil palm biomass [17]. Several studies have been conducted to determine the thermal efficiency of different types of palm biomass, such as palm kernel shells and palm fronds. However, the specific comparisons with LPG in the form of thermal energy output have not been discussed thoroughly and in detail. While research has been conducted on the heat transfer efficiency of biomass, a direct equivalence with LPG remains unexplored [18].

In addition, there is a significant lack of empirical data on optimal operational parameters such as temperature, time, and thermal conductivity of biomass in pyrolysis and gasification processes to improve energy yield and syngas production. Some of the main findings and gaps include temperature, which is fundamental to observing as an important parameter that can affect the yield and composition of pyrolysis and gasification products. Generally, higher temperatures can increase gas yield and improve syngas quality [19–21]. However, the exact optimum temperature varies depending on the type of biomass and the specific process used. A study has been conducted on bamboo waste that found an optimal temperature of 550°C for pyrolytic polygene ration [22], while another study on neem seeds found that a temperature of 375°C is the optimal temperature to produce bio-oil and biochar [23]. Then time, where the length of the pyrolysis process time also has a significant impact on product results and quality. In contrast, longer residence times tend to increase the calorific value of charcoal but decrease the yield [24]. However, the specific optimal time is not consistently found in various studies, so further research is needed to determine a more standardized time [23,24]. Thermal conductivity, another crucial factor in pyrolysis, influences heat transfer within biomass particles, thereby affecting overall process efficiency, [21]. Studies have shown that thermal conductivity increases with temperature to a certain point and then stabilizes [25]. Moreover, a thermos-kinetic study for EFB has been conducted by Melvin et al. 2024 EFB was determined at 8.8 wt.% of moisture content for pyrolysis and gasification [26].

The use of fine powder from oil palm EFB as a primary fuel in an integrated biomass pyrolysis and gasification process within a cylindrical bio-stove has not yet been extensively explored. The FEA is a tool that was recently conducted to determine the thermal conductivity of biomass [4]. However, more empirical data with standardized research is needed to determine the best operational parameters for EFPB, which could serve as a reference for other biomass types to maximize energy yield and syngas production. Based on the aforementioned research gap and SDG goals, it can be concluded that this research of generating heat energy from the fine powder of EFB using a cylinder bio stove and determining the thermal conductivity value of EFB by using FEA is significant. This research also contributes valuable insights into the integrated pyrolysis and gasification process, helping to optimize syngas production Furthermore, the findings also provide a basis for assessing the duration of heat energy production in bio-stoves fueled by fine-powdered EFB can be utilized as an ignition source to produce heat energy for use in water boilers, pyrolysis machine reactors, community cooking equipment, and others.

## 2. Materials and method

### 2.1. Experiment procedure

Experiments were conducted in a state-of-the-art materials laboratory at Yogyakarta State University. The flowchart below outlines the experiment process (Fig. 2).

### 2.2. Physical properties of material

The research utilized a fine powder of oil palm empty fruit bunches (EFB), sourced from the Sumatra region of Indonesia Fig. 1. The EFB fine powder was subjected to rigorous testing in a laboratory, and the resulting data revealed insightful findings, as shown in Table 1 below. According to research by Pornwimon et al. (2021), the values of cellulose, hemicellulose, and lignin differ from those are different with the value are different with the value used in this experiment, as shown in Table 1 below. Therefore, the EFB value varies and must be analyzed before conducting experiments [27].

Based on research by Sukiran et al. (2020) [28], the high moisture content in EFB significantly reduces its calorific value and energy density. In general, lower moisture content enhances the calorific value, energy yield, and mechanical properties of EFB products. Therefore, this research utilizes moisture levels of 9 %, 11 %, and 14 % to analyze their impact, providing more precise insights into moisture behavior for future research.

### 2.3. Fill up the fine powder of oil palm empty fruit bunch (EFB) into the bio stove

According to the research conducted using wood powder by Wagiran et al. and Mujiyono et al. [1,29], this research follows the same method and the same bio-stove; however, used different biomass materials which is the fine powder of EFB with a moisture content of 9 %, 11 %, and 14 %. The total weight of the fine powder of EFB that has been put into the bio-stove is 18kg. The bio-stove functions as an integrated pyrolysis and biomass gasification system, also known as a gasifier. The following are the steps taken to fill the fine powder of EFB into the bio-stove.

First, the fine powder of EFB with a moisture content of 9 %, 11 %, and 14 % is systematically added to the bio-stove cylinder in three layers. The fine EFB powder with a 9 % moisture content is poured into the gasifier chamber of the stove's first or bottom section. Next, the gas generator is fitted with the first load-bearing disc. The second/middle part of the bio-stove is poured with the fine powder of EFB with a moisture content of 11 %. Then, the second load-bearing plate is inserted into the gas generator. The fine EFB powder with a 14 % moisture content is put into the third/top portion, which is then stacked similarly to the first section. The purpose of load-bearing discs is to keep oil palm

Fig. 1. Oil palm (A), Oil palm empty fruit bunches (B), Fine powder of oil palm empty fruit bunches (EFB/EFB) (C).

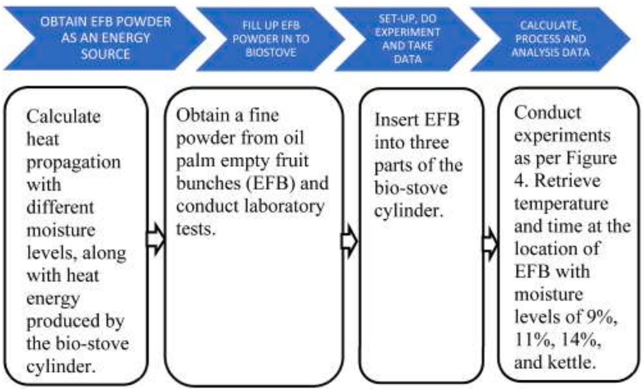


**Fig. 2.** Flow diagram of the experiment integrated biomass pyrolysis and gasification from fine powder of oil palm empty fruit bunch powder (EFB) on the bio-stove cylinder.

**Table 1**
Composition of fine powder from oil palm empty fruit bunch (EFB).

| Condition | Value as per experiment | Value as per Pornwimon et al. 2021 [27] | Unit |
|---|---|---|---|
| Cellulose | 33.8 | 25.02 | % |
| Hemicellulose | 25.2 | 38.16 | % |
| Lignin | 20.5 | 36.82 | % |
| Moisture Content | 9, 11, 14 | | % |

empty fruit bunches from collapsing and to preserve their shape. After the top cover is put together and attached to the pressing unit, the unit is pushed until the required column height is reached. Next, the aisle—a tube-shaped opening in the center of the raw material—is created by removing the large and small middle pipes from the chamber before turning on the burner. Through the gasifier's entrance, oxygen will enter and move into the chamber's gaps. A fire ignited in the alley after someone inserted fire paper into the gasifier's input. The compressed fine powder of oil palm EFB is pyrolyzed because of the rising temperature in the alley, and the pyrolysis temperature has been attained. Fig. 3 shows a bio-stove that has been filled with a fine powder of empty oil palm fruit bunches that have been pressed and covered with a plate cover and are then ready to be carried out for experiments to produce syngas.

The fine powder of EFB with a moisture content of 9 % is poured into the gasifier chamber at the bottom section of the stove, followed by the insertion of the first load-bearing disc inserted into the gas generator. Next, the second/middle part of the bio-stove is poured with the fine powder of EFB with a moisture content of 11 %, and then the second load-bearing plate is inserted into the gas generator. The third/top section is poured with fine powder of EFB with a moisture content of 14 % and then stacked like the first section. Load-bearing discs are used to

**Fig. 3.** Bio-stove containing the fine powder of oil palm empty fruit bunches (EFB).

maintain the shape of oil palm empty fruit bunches and prevent oil palm empty fruit bunches from collapsing. Finally, the top cover is assembled and connected to the pressing unit, which is then pressed until it reaches the desired column height.

### *2.4. Experimental work*

Fig. 4 shows the experimental setup, where a bio-stove filled with the fine powder of EFB is equipped with a temperature measuring device (thermocouple) with the following notations, location, and depth:

1. T1, T2, and T3 are immersed in a fine powder of EFB with 9 % moisture content. The depths of T1, T2, and T3 are 40 mm, 80 mm, and 120 mm, respectively.
2. T4, T5, and T6 are immersed in a fine powder of EFB with 11 % moisture content. The depths of T4, T5, and T6 are 120 mm, 80 mm, and 40 mm, respectively.
3. T7, T8, and T9 are immersed in a fine powder of EFB with 14 % moisture content. The depths of T7, T8, and T9 are 120 mm, 80 mm, and 40 mm, respectively.
4. T10 in Flame Area.

A digital thermometer is carefully placed on the kettle to measure the temperature of the water. Additionally, a stopwatch is used to record the time required for the kettle to reach the boiling point, which is the temperature of 100°C. Meanwhile, a thermocouple T1-T10 is connected to a data logger to monitor and record temperature variations throughout the pyrolysis process. The thermocouple was used to record temperature and time data during the pyrolysis process. The thermocouple is strategically positioned in the bio-stove to monitor the temperature propagation in a fine powder of EFB. As the pyrolysis process progresses, syngas is produced through integrated gasification. The data collected from the thermocouple and data logger ensures accurate and comprehensive monitoring of the temperature and time data during the pyrolysis process.

### *2.5. FEA model*

The heat propagation and thermal conductivity of fine powdered EFB in the pyrolysis process were determined by prior project studies using ANSYS software and FEA models with boundary conditions, as shown in Fig. 5 [30].

### *2.6. Chemical reaction details and specific operating parameters of biomass gasification and pyrolysis.*

Based on Basu and Shivpal Verma et al. [10,31], the following are the chemical reaction details and specific operating parameters of Biomass gasification and pyrolysis:

1. Drying stage/torrefaction (100–200°C)

Wet biomass → Dry biomass + $H_2O(g)$
Initial water content: optimal <20 %
Heating rate: 5–10°C/min
Residence time: 20–30 min

2. Pyrolysis stage (200-500°C)

a) Cellulose Decomposition (240–350°C)

$(C_6H_{10}O_5)\ n \rightarrow n(C_6H_{10}O_5)$
$C_6H_{10}O_5 \rightarrow C_6H_8O_4 + H_2O$
$C_6H_8O_4 \rightarrow 3CO + 2H_2 + CH_4 + C$

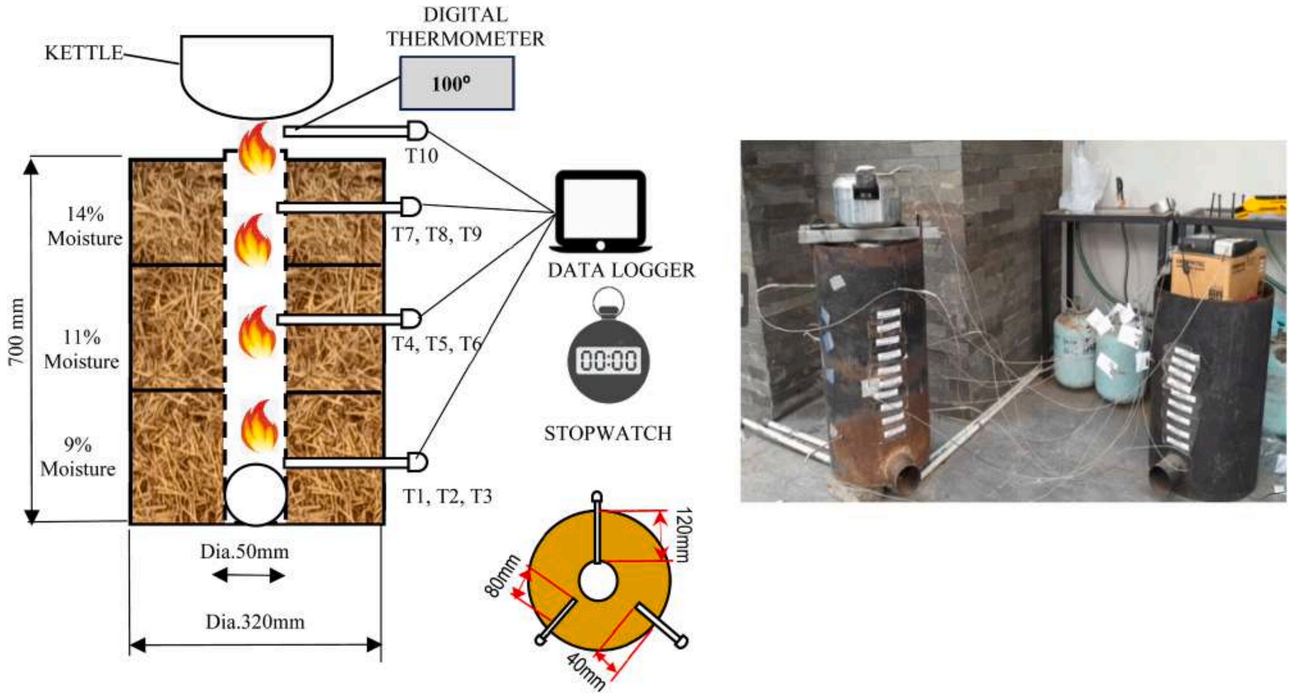


Fig. 4. Schematic diagram of experimental and experimental photo before the bio stove works.

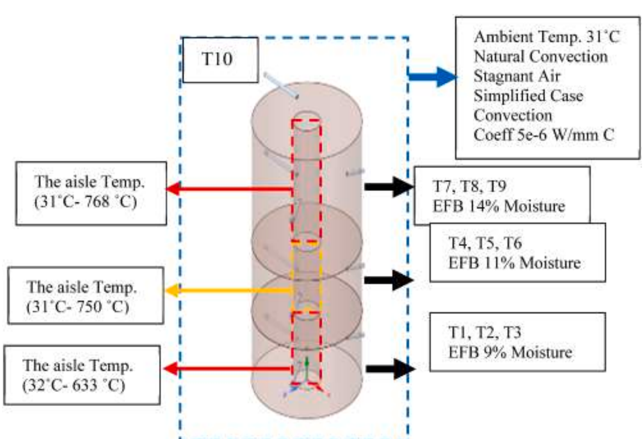


Fig. 5. FEA boundary conditions on bio-stove containing the fine powder of oil palm empty fruit bunches (EFB).

a) Hemicellulose Decomposition (200–260°C)

$(C_5H_8O_4)n \rightarrow n(C_5H_8O_4)$
$C_5H_8O_4 \rightarrow 2CO + CO_2 + H_2 + CH_4$

a) Lignin Decomposition (280–500°C)

$C_9H_{10}O_2 \rightarrow CO + C_8H_{10}O$
$C_8H_{10}O \rightarrow CO + C_7H_{10}$

3. Oxidation stage (700–1500°C)

Partial Combustion Reaction
$C + \frac{1}{2}O_2 \rightarrow CO$
$C + O_2 \rightarrow CO_2$
$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

4. Reduction stage/gasification (700–1000°C)

a) Boudoir's reaction

$C + CO_2 \rightleftharpoons 2CO$

a) Water-gas reaction

$C + H_2O \rightleftharpoons CO + H_2$

a) Water-gas Shift Reaction

$CO + H_2O \rightleftharpoons CO_2 + H_2$

a) Methanation Reaction

$C + 2H_2 \rightleftharpoons CH_4$

## 3. Results and discussion

The bio-stove filled with fine powder of oil palm EFB has been proven functional and produces stable heat energy after burning, as demonstrated by the experimental results in Fig. 6. A water boiling test was carried out at room temperature, using different volumes of water ranging from 1 liter to 4.5 liters. The experiment measured the time and temperature until the water reached its boiling point of 100°C. Table 2 and Fig. 7 present experimental results that showed that the greater the volume of water, the more energy is required to be boiled to reach a temperature of 100°C.

The research found that the energy value produced by boiling 1.5 liters of water with a bio-stove containing fine powder of EFB is 110 Kcal in 6 min, based on experiments conducted by Mujiyono et al. [1]. It

**Fig. 6.** Photo of bio-stove in operation.

**Table 2**
The energy generated by bio-stove for boiling water from 35 to 100°C at a specific time.

| Water Volume (Liter) | Energy (Kcal) | Time (Minutes) |
|---|---|---|
| 1 | 68.26 | 4.48 |
| 1.5 | 110.22 | 6.36 |
| 2 | 136.52 | 7.40 |
| 2.5 | 170.65 | 9.50 |
| 3 | 204.78 | 11.01 |
| 4 | 273.05 | 20.55 |
| 4.5 | 307.18 | 16.48 |

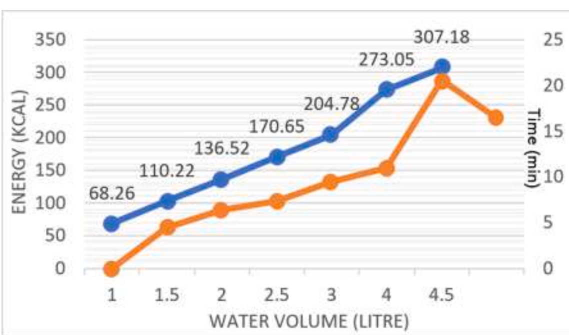


**Fig. 7.** Experimental result graphic energy released by biomass to boil water at 100 °C.

shows that the energy released by a stove with LPG is 180 Kcal and a stove with Sawdust is 167 Kcal in 6 min to boil 1.5 liters of water respectively as shown in Fig. 8. This finding indicates that a bio-stove containing fine powder of EFB can produce energy almost equivalent to a stove with LPG. In addition, a study by Dewanjaya et al. [2] shows that the EFB Pellets price is IDR 2000 per kg and the LPG 3 kg price is

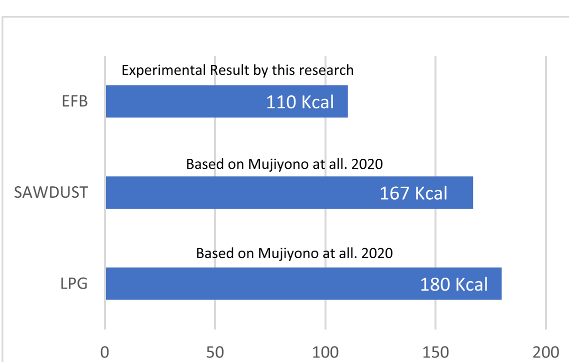


**Fig. 8.** The energy is released by the bio-stove to boil 1500 mL of water in 6 min.

IDR 7000 per kg accordingly if it is assumed EFB and LPG per kg in the stove will produce heat energy released is 1 Kcal and hence the price of EFB stove generated heat energy released is 110 Kcal x IDR 2000 = IDR 220,000 and the price of LPG stove generated heat energy released is 180 Kcal x IDR 7000 = IDR 1,260,000. Based on these calculations, an EFB-powered bio-stove is more economical than an LPG stove.

Additionally, Figs. 9–12 present experimental results demonstrating the heat propagation in the bio-stove. These experiments were conducted using fine powder of oil palm empty fruit bunch, with moisture levels of 9 %, 11 %, and 14 %, respectively. The figures also illustrate the temperature of the flame produced by the bio-stove.

Fig. 9 shows that the torrefaction process occurred at temperatures of 100°C and above, the T3 = 101°C at 47 min (0.78 h), T2=101°C at 95 min (1.58 h), and T1=102°C at 147 min (2.45 h). After that, the pyrolysis process occurred at temperatures of 200°C and above, T3=206°C at 65 min (1.08 h), T2=213°C at 123 min (2.05 h), and T1=202°C at 173 min (2.88 h). Followed by the gasification process occurring at temperatures of 700°C and above, the T3=700°C at 179 min (2.98 h). Meanwhile, T2 and T1 do not reach temperatures above 700°C. Based on these findings, the pyrolysis and gasification process occurred throughout the fine powder of the EFB area with a moisture content of 9 % for 4.5 h on thermocouple T3. Meanwhile, torrefaction and pyrolysis processes occurred on thermocouples T2 and T1. This information provides valuable insights into the heat propagation behavior of fine powder EFB with 9 % moisture content in a bio-stove.

Fig. 10 shows that the torrefaction process occurred at temperatures of 100°C and above, the T4 = 105°C at 37 min (0.62 h), T5=102°C at 173 min (2.88 h) and T6 do not reach temperatures of 100°C and above. After that, the pyrolysis process occurred at temperatures of 200°C and above, the T4=214°C at 51 min (0.85 h), T5=202°C at 219 min (3.65 h), and T6 do not reach temperatures of 200°C and above. Followed by the gasification process occurring at temperatures of 700°C and above, T4=703°C at 119 min (1.98 h), T5 and T6 do not reach temperatures above 700°C. Based on these findings, the pyrolysis and gasification process occur throughout the fine powder of the EFB area with a moisture content of 9 % for 4.5 h on thermocouple T4. Meanwhile, torrefaction and pyrolysis processes occurred on thermocouple T5 whereas, T6 did not reach temperatures above 100°C. This information is valuable in understanding the behavior of heat propagation in the fine powder of EFB with a moisture content of 11 %.

Based on the data presented in Fig. 11, it clearly shows that the torrefaction process occurred at temperatures of 100°C and above, the T7 = 102°C at 41 min (0.68 h), T8=101°C at 121 min (2.02 h) and T9=102°C at 149 min (2.48 h). After that, the pyrolysis process occurred with started at 200°C and above, T7=208°C at 61 min (1.02 h), T8=200°C at 169 min (2.82 h), and T9=203°C at 187 min (3.12 h). Followed by the gasification process occurring at temperatures of 700°C and above, the T7=703°C at 157 min (2.62 h). Meanwhile, T8 and T9 do not reach temperatures above 700°C. These findings indicate that pyrolysis and gasification processes occur solely in the T7 thermocouple area for 4.5 h, meanwhile, torrefaction and pyrolysis processes occurred on the thermocouple in the T8 and T9 areas. This information plays a vital role in understanding the behavior of the fine powder of EFB with a moisture content of 14 % during heat propagation.

The graph in Fig. 12 illustrates the temperature changes of the flame generated by the bio-stove over time. Initially, the flame's temperature surpassed 400°C within the first minute and continued to rise, reaching its peak temperature of 830°C in 13 min. After that point, the temperature fluctuated, eventually dropping to 790°C in 133 min (2.2 h). At 135 min (2.25 h), the flame temperature once again surpassed 790°C, followed by another fluctuation until minute 270 (4.5 h) at a temperature of 535°C.

In conclusion, bio-stove with a fine powder of EFB can maintain a temperature of 400-800°C for 4.5 h. This data can be beneficial for comprehending the flame's temperature created by a bio-stove as a source of heat energy for water steam boilers, pyrolysis machine

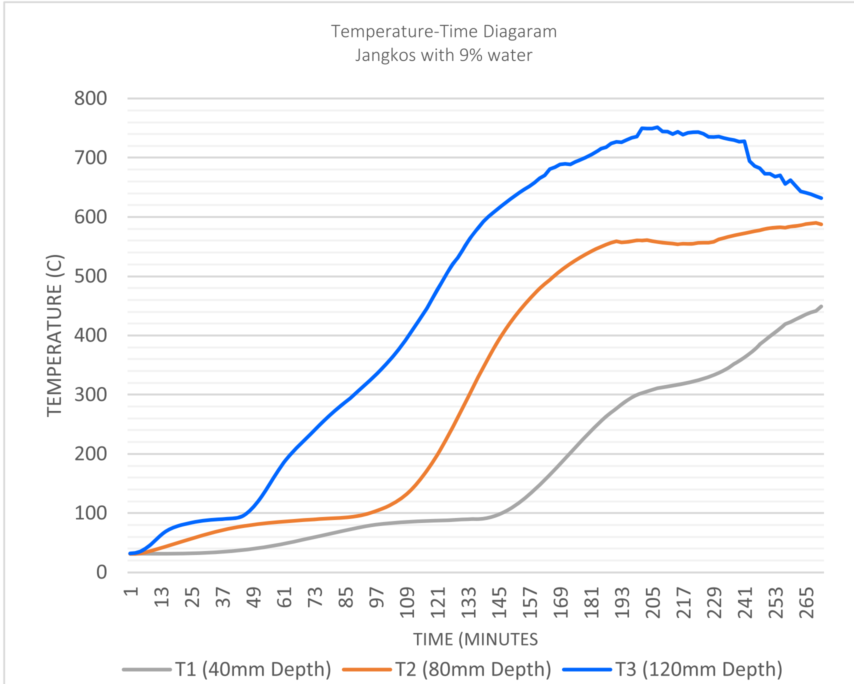


**Fig. 9.** Experimental result of the plot temperature-time graph for the fine powder of EFB with 9 % moisture in bio-stove.

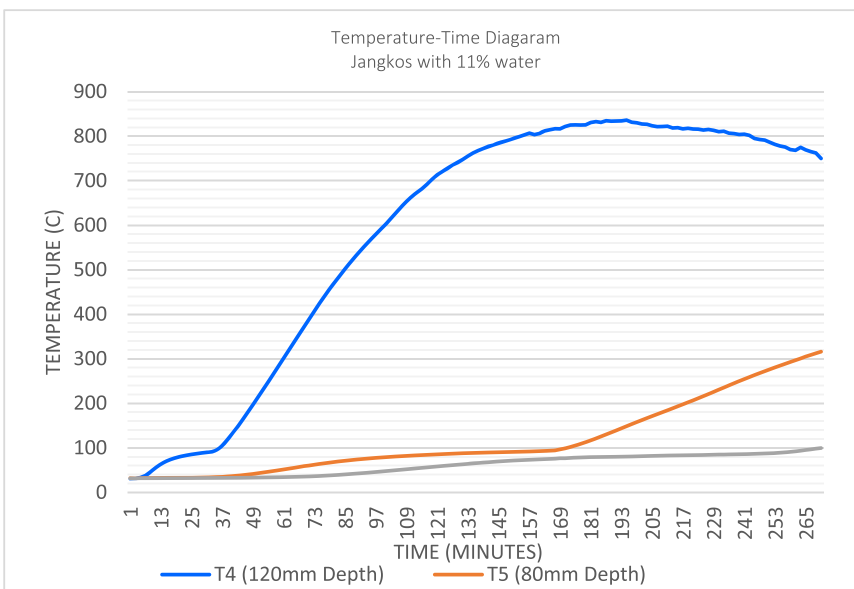


**Fig. 10.** Experimental result of the plot temperature-time graph for the fine powder of EFB with 11 % moisture in bio-stove.

reactors, public cooking utensils, and other applications.

The simulation results of FEA findings in Fig. 13 agree, demonstrating that the thermocouple is immersed in a fine powder of EFB with 9 %, 11 %, and 14 % moisture content at 120mm depth, showing temperatures 632°C, 750°C, and 768 °C which indicates that a perfect pyrolysis and gasification process occurs which produces syngas, and this is the same as that shown in the experimental results.

Furthermore, as shown in Figs. 14–16, the results of the experiment and FEA simulation show that the thermal conductivity values for fine powder of EFB with moisture content 9 %, 11 %, and 14 % are K = 3 W/m.C, K = 0.2 W/m.C and K = 0.8 W/m.C, respectively. Notably, the fine powder EFB with 9 % moisture content exhibits the highest conductivity value (K = 3 W/m·°C), supporting the conclusion that the pyrolysis and gasification processes occur efficiently in this condition.

The FEA simulation results in Fig. 13 aligned with experimental findings, confirming that thermocouples immersed in fine powder EFB with 9 %, 11 %, and 14 % moisture content at a depth of 120 mm recorded temperatures of 632°C, 750°C, and 768°C, respectively. These temperatures indicated a successful pyrolysis and gasification process that produces syngas, consistent with experimental results. Additionally, heat transfer occurs from the flame to the fine EFB biomass, affecting temperature distribution within the stove's layers. The simulation also verifies that torrefaction, pyrolysis, and gasification processes take place, as shown in Fig. 17.

Furthermore, as illustrated in Figs. 14–16, the results of the experiment and FEA simulation show that the thermal conductivity values for

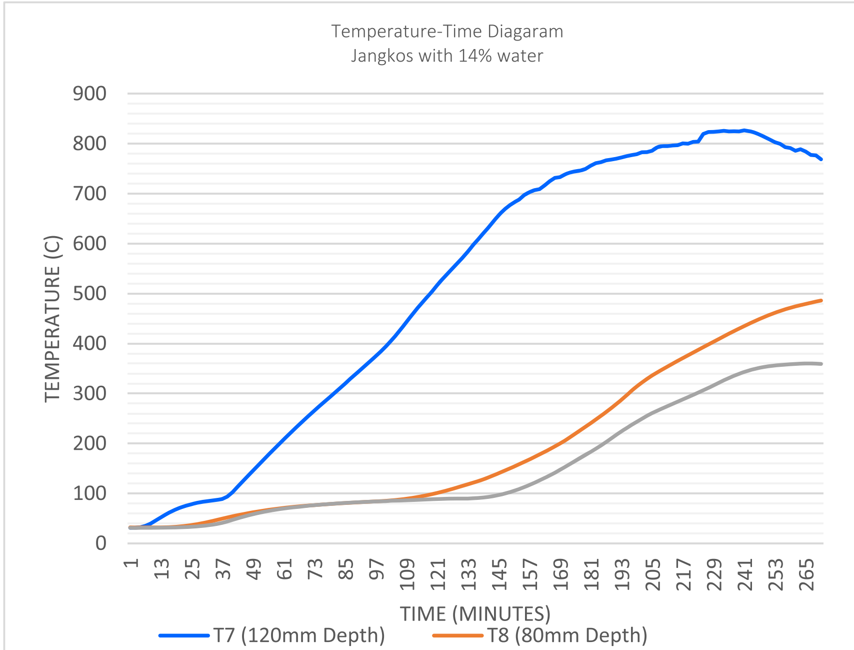


**Fig. 11.** Experimental result of the plot temperature-time graph for the fine powder of EFB with 14 % moisture in bio-stove.

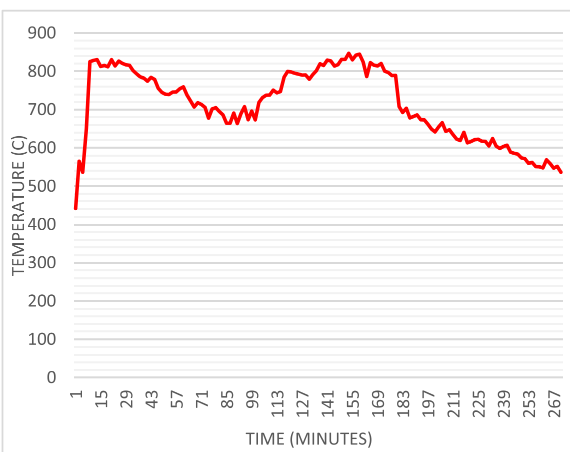


**Fig. 12.** Temperature-time plot graph for flame produced by bio-stove with the fuel of the fine powder of EFB.

fine powder of EFB with moisture content 9 %, 11 %, and 14 % are K = 3 W/m.C, K = 0.2 W/m.C and K = 0.8 W/m.C respectively. In the fine powder of EFB with a moisture content of 9 %, the most considerable conductivity value is K = 3 W/m.C. This value is determined by FEA based on an approach to the experimental result of the temperature-time plot for fine powder EFB with 9 %, 11 %, and 14 % moisture in the bio-stove.

Fig. 17 illustrates the combustion process, which begins with igniting fire paper or another fuel source in the stove chamber. These initiates heat transfer to the fine powder EFB, triggering the torrefaction (biomass drying) process at 100–200°C. After that, the pyrolysis process starts at a temperature of 200–500°C and generates syngas where the syngas as fuel goes to the chamber of the stove then the mixing process of fire three angles theory (Oxygen + Heat + Fuel) occurs which causes combustion. Finally, the gasification process started at a temperature of 800–1000°C and generated biochar. After 4.5 h, the process pyrolysis and gasification processes were completed, and the stove would not produce fire anymore whereas the biochar and torrefied EFB of biomass were shown in the picture of the experiment.

In addition, heat transferred was found from flame on the combustion of the stove to the fine powder of EFB which had occurred during the process of torrefaction, pyrolysis, and gasification. Thus, the thermal conductivity of EFB plays a crucial role in syngas production of the pyrolysis process, where Cellulose, Hemicellulose, and Lignin will experience thermal reactions at certain temperatures and layer/distance.

Based on these findings, it can be concluded that the pyrolysis and

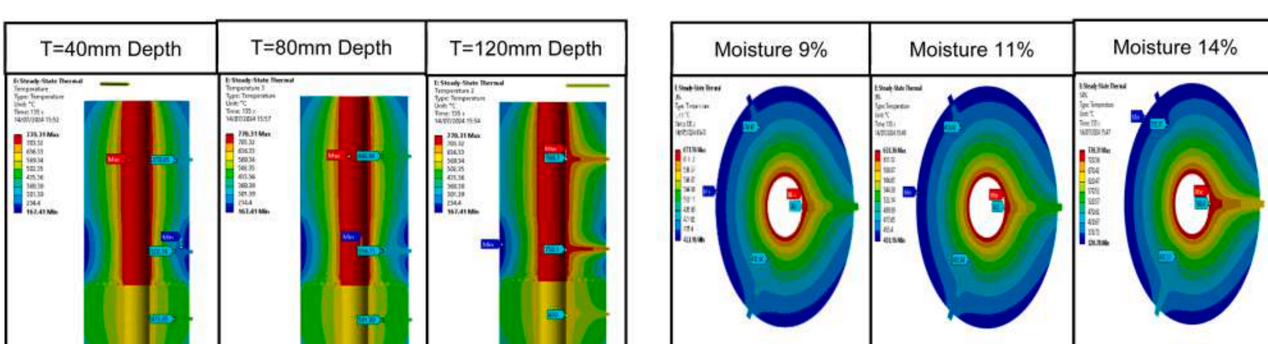


**Fig. 13.** FEA result for Axial-Section Contour Temperature and Cross-Section Contour Temperature in EFB stove.

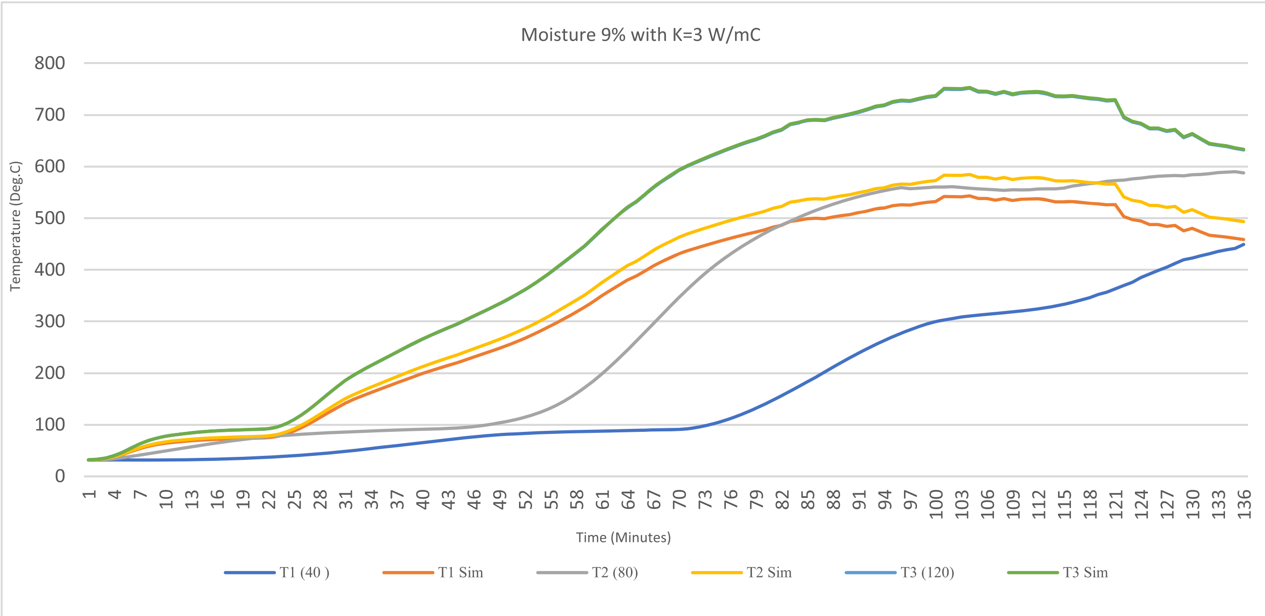


**Fig. 14.** FEA result simulation and experimental results combined for EFB in a stove with 9 % moisture.

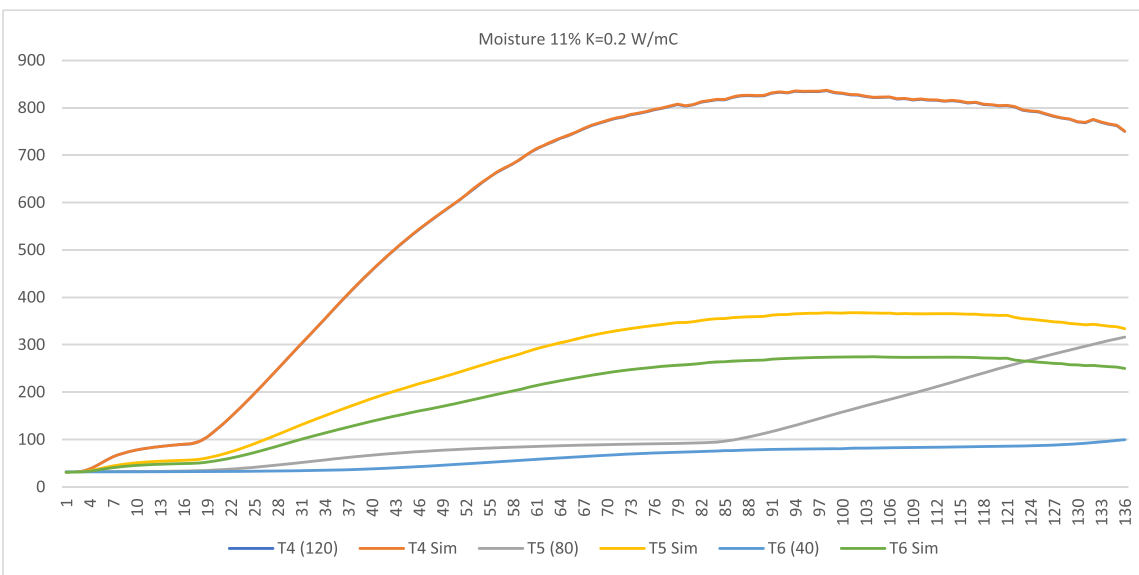


**Fig. 15.** FEA result simulation and experimental results combined for EFB in a stove with 11 % moisture.

gasification processes in the EFB bio-stove are highly effective.

## 4. Conclusion

The research shows that bio-stove utilizing fine powder EFB with 9 %, 11 %, and 14 % moisture content is functional and produces stable heat energy, maintaining temperatures between 400–800°C for 4.5 h with the thermal conductivity values for 9 %, 11 %, and 14 % Moisture are K = 3 W.m/C, K = 0.2 W.m/C and K = 0.8 W.m/C, respectively. In addition, the findings provide a comprehensive understanding of the heat energy generated by bio-stoves utilizing the fine powder of EFB as fuel with the heat energy generated is 110 Kcal which is released in ±6 min to boil 1.5 liters of water. Compared to research conducted by Mujoyono et al. (2020) [1] reporting that the result is nearly equivalent to an LPG stove in which heat energy generated is 180 Kcal of energy released in ± 6 min. Furthermore, based on research conducted by Dewanjaya et al. [2], EFB pellets cost IDR 2000 per kg, whereas LPG costs IDR 7000 per kg. Assuming that both fuels produce 1 Kcal per kg, the cost of generating 110 Kcal with an EFB stove is IDR 220,000 (110 Kcal × IDR 2000) while producing 180 Kcal with an LPG stove costs IDR 1,260,000 (180 Kcal × IDR 7000). As a result, these findings indicate that EFB-based bio-stoves offer a more economical alternative to LPG stoves.

Future researchers are recommended to study the integration of bio-stoves into existing energy systems or to examine long-term durability and environmental implications especially emission, waste management, and life cycle. Meanwhile, this research contributes to the development of more efficient and sustainable energy sources, applicable to water boilers, pyrolysis machine reactors, and community cooking tools.

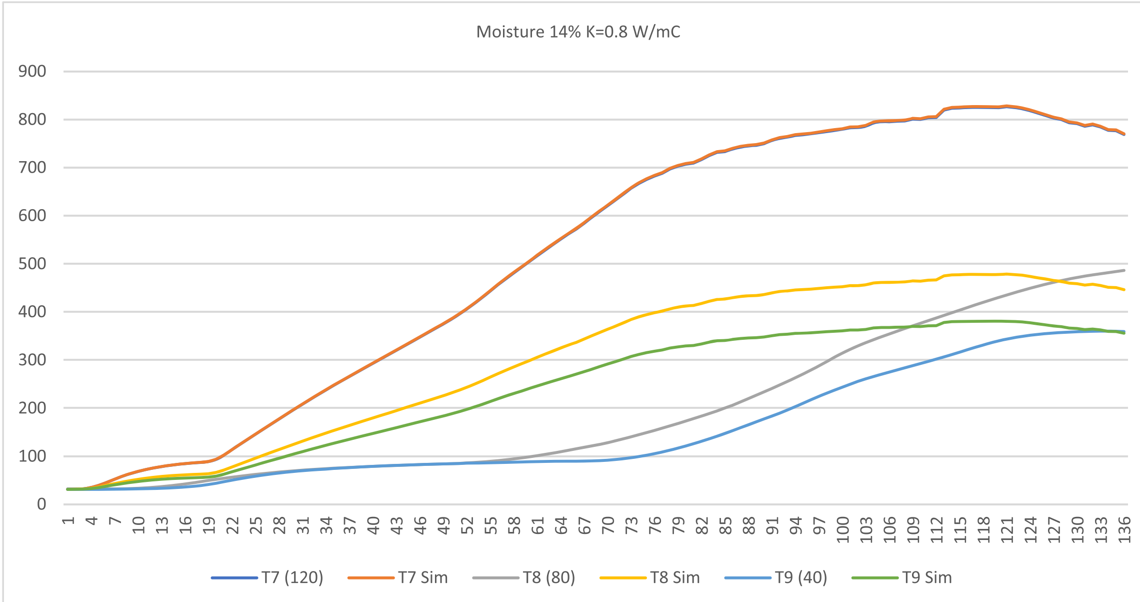


**Fig. 16.** FEA result simulation and experimental results combined for EFB in a stove with 9 % moisture.

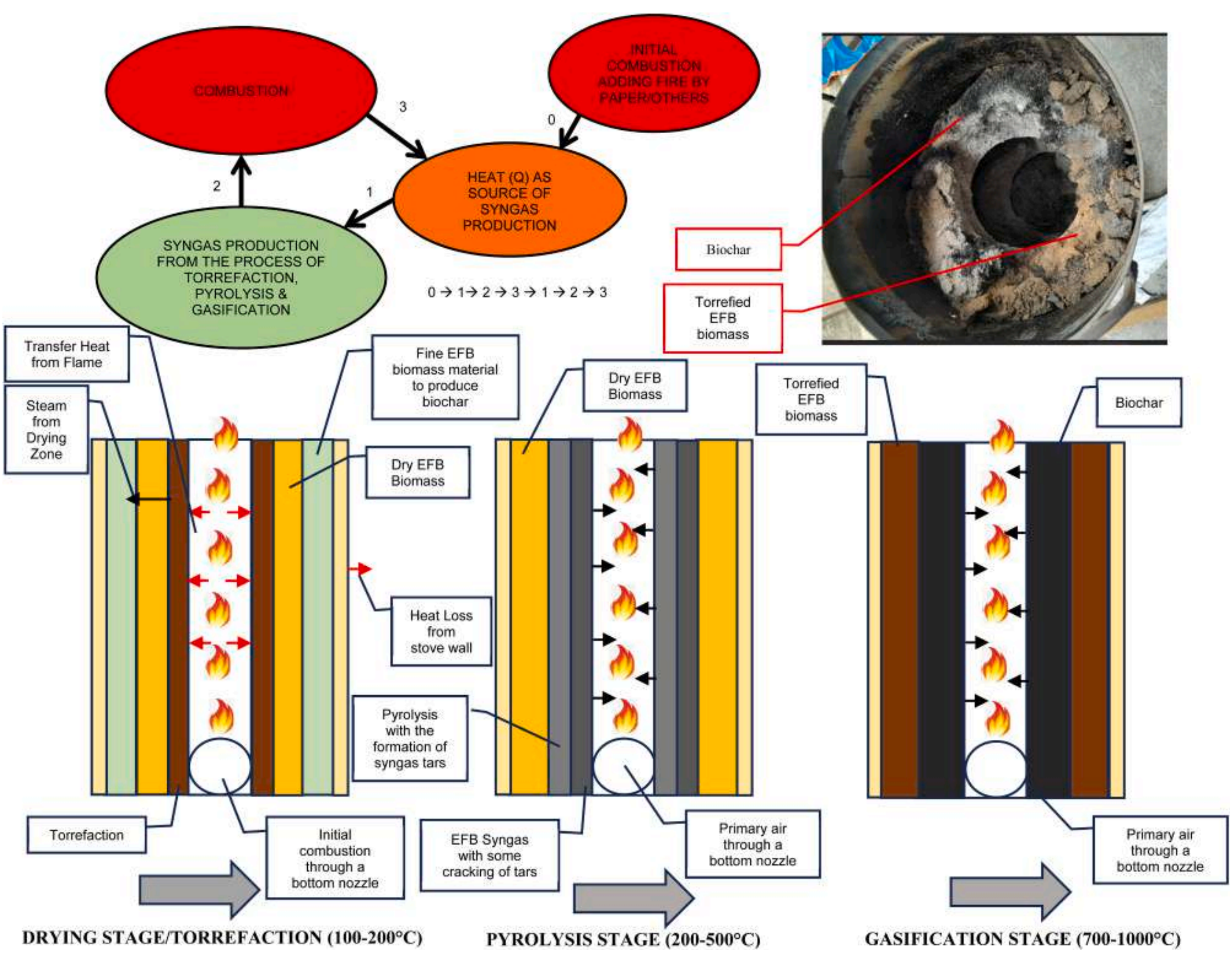


**Fig. 17.** Process cycle, schematic diagram, and experimental setup for EFB stove.

## CRediT authorship contribution statement

**Paul David Rey:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Mujiyono:** Supervision, Conceptualization. **Didik Nurhadiyanto:** Supervision, Conceptualization. **Helmi Kusuma Perdana:** Validation, Formal analysis, Data curation, Conceptualization. **Eddy Rusly:** Resources.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rineng.2025.104741.

## Data availability

Data will be made available on request.

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