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ORIGINAL RESEARCH ARTICLE

# Torrefaction of bamboo pellets using a fixed counterflow multibaffle reactor for renewable energy applications

**W. Hidayat[1,*], B.A. Wijaya[2,3], B. Saputra[1], I.T. Rani[2], S. Kim[2], S. Lee[2], J. Yoo[2], B.B. Park[3], L. Suryanegara[4], M.A.R. Lubis[4]**

[1]*Department of Forestry, Faculty of Agriculture, University of Lampung, Jl. Prof. Dr. Ir. Sumantri Brojonegoro No.1, Lampung 35141, Indonesia*

[2] *Climate Change Research Division, Korean Institute of Energy Research, Daejon, 34129, Republic of Korea*

[3] *Department of Environment and Forest Resources, College of Agriculture and Life Science, Chungnam National University, 99 Daehak-ro, Daejeon, 34134, Republic of Korea*

[4] *Research Center for Biomass and Bioproduct, National Research and Innovation Agency. Jl. Raya Jakarta-Bogor Km. 46, Cibinong, Bogor, 16911, Indonesia*

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## ABSTRACT

**BACKGROUND AND OBJECTIVES:** The decreasing availability of fossil fuels requires the adoption of renewable energy sources that facilitate the mitigation of greenhouse gas emissions. Meeting Indonesia's goal of achieving a 23 percent mixed energy composition by 2025 through co-firing demands a substantial increase in the availability of renewable energy sources. Bamboo is a valuable biomass resource because of its fast growth rate and potential for energy production. Innovative processes like torrefaction are necessary to improve the quality of biomass due to its challenging low density and hydrophilic properties. The objective of this study is to evaluate the characteristics of torrefied bamboo pellets made from *Gigantochloa pseudoarundinacea* by using a fixed counter-flow multi-baffle reactor. This study aims to investigate the properties and viability of torrefied G. pseudoarundinacea pellets for solid fuel applications to fill existing knowledge gaps about this technology's potential.

**METHODS:** A fixed counter-flow multi-baffle reactor was used to torrefy *G. pseudoarundinacea* bamboo pellets. The baffles in the reactor column held the pellets, while hot gas flowed through them. Torrefaction was conducted at 280 degrees Celsius with a 3–5 minutes resident time, and the gas flow rate was 4.25 cubic meters per minute. Torrefied pellets at the column bottom were counted as the first cycle. Three cycles of torrefaction were used, and each cycle was evaluated. The second and third cycles used torrefied pellets from the first and second cycles. The physical, chemical, and bioenergetic properties of the pellets before and after torrefaction were evaluated.

**FINDINGS:** The bamboo pellets' physical, chemical, and thermal properties changed significantly after torrefaction. Torrefaction at 285 degrees Celsius produced 78.5 percent of the production yield, according to thermogravimetric and derivative thermogravimetric analyses. Lightness, red/green, and yellow/blue chromaticity decreased, indicating darker, better solid fuel pellets. Torrefaction in the third cycle reduced moisture content by 99.8 percent. The lower moisture content reduced fungal growth, and improvinged biomass transport and storage. Torrefaction also raised the bamboo pellets' calorific value and physical and mechanical properties. The highest calorific value of 21.62 megajoules per kilogram was obtained after the third cycle of torrefaction, and it was 16.6 percent higher than that of raw pellets. Torrefaction improved pellet grindability and combustion by decreasing density and compressive strength. Torrefaction increased ash, volatile matter, and fixed carbon. The ultimate analysis showed increased carbon and reduced nitrogen, hydrogen, and oxygen, improving solid fuel quality, energy density, and combustion emissions. According to a Fourier-transform infrared analysis, torrefaction caused extractive and hemicellulose degradation and lignin increase. The chemical analysis showed that temperature and residence time degraded hemicellulose and increased lignin in the torrefied pellets.

**CONCLUSION:** The torrefaction process using a fixed counter-flow multi-baffle reactor demonstrated the enhanced properties of *G. pseudoarundinacea* bamboo pellets for their application as solid fuel. The study's findings contribute to the comprehension of torrefaction and the enhancement of conditions for producing superior biomass products. These findings have implications for exploring the potential applications of torrefaction in diverse industries and energy sectors.

| NUMBER OF REFERENCES | NUMBER OF FIGURES | NUMBER OF TABLES |
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*Corresponding Author:
Email: *wahyu.hidayat@fp.unila.ac.id*
Phone: +6282 2115 48516
ORCID: 0000-0002-6015-1623

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## INTRODUCTION

Tropical forests contribute essential ecological, climate, and socioeconomic benefits to global and local people in nations like Indonesia. The high biodiversity in Indonesian forests is a source of biomass. Forest-based biomass is an alternative source of renewable energy (Favero *et al.,* 2020). Biomass refers to any organic matter derived from plants through photosynthesis, and it can exist in the form of products or waste (Saputra *et al.,* 2022; Hazbehiean *et al.,* 2022; Santoso *et al.,* 2023; Samimi and Monsouri, 2023). The high potential for biomass to become a global energy supply could further reduce fossil fuel use, which has decreased over the years (Dhanasekar and Sathyanathan, 2023). Indonesia's biomass potential is approximately 146.7 million tons/year, equal to 470 gigajoule/year (Rhofita *et al.,* 2022). Biomass is believed to support greenhouse gas reduction in the future (Samimi and Shahriari-Moghadam, 2021). From 2000 to 2013, biomass accounted for approximately 5.8 percent (%) to 8.9% of global electricity production (Bonechi *et al.,* 2017). Global biomass production in 2016 was approximately 2 x $10^{11}$ tons (dry carbon bases), making it the most abundant renewable resource on Earth. By 2050, it is predicted that 3,000 terawatt hours (TWh) of electricity could be generated from biomass, avoiding the annual emission of 1.3 billion tons (Bt) of carbon dioxide ($CO_2$) equivalent (Gielen *et al.,* 2019). Thus, there is significant potential for utilization. In 2010, woody biomass constituted approximately 9% of global primary energy consumption and 65% of global renewable primary energy consumption (Lauri *et al.,* 2014). The disadvantages of woody biomass include its potential impact on traditional wood users, forestland usage, and management difficulties. The increased utilization of wood for bioenergy could potentially result in underestimation of log volume and associated concerns within the wood market. As a developing nation, Indonesia is susceptible to climate change impacts. The country ratified the Paris Agreement with Law No. 16 in 2016. Indonesia has demonstrated its dedication to mitigating greenhouse gas (GHG) emissions by reinforcing its commitment in the Nationally Determined Contributions (NDC) document (Suroso *et al.,* 2022). Decision 1/Meeting of the Parties to the Paris Agreement (CMA) 3 requires Parties to revise and strengthen their NDC-2030 target to meet the Paris Agreement's temperature goal by 2022. According to this mandate, Indonesia submitted Enhanced NDC to the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat on September 23, 2022, with an emission reduction target of 31.89% on its own efforts and 43.20% with international support. This Enhanced NDC is a transition to Indonesia's Second NDC, which aligns with the Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR) 2050 and aims for net zero emissions by 2060 or sooner (Government of Indonesia, 2022). Biomass-coal co-firing will help Indonesia meet its NDC and net zero emission conditions by replacing coal fuel with biomass waste to reduce organic waste. New technologies such as carbon capture storage (CCS) must be considered to recover/capture the slightly produced carbon from co-firing to generate net zero carbon. This scheme aims to facilitate the realization of the Paris Agreement's objective of attaining net zero emissions by the latter half of this century (Yulianto *et al.,* 2022). Indonesia aims to achieve a 23% share of mixed energy sources by the year 2025. Biomass is significant due to its utilization in co-firing. Nevertheless, the issue of low supply persists in the present day (IESR, 2022). Bamboo, a member of the grass family, is a plant native to Asia, Africa, and South America. The growth rate of bamboo varies among species; however, bamboo generally exhibits rapid maturation. Bamboo is also adaptable to various climates, and its superior properties contribute to its widespread cultivation (Kang *et al.,* 2019). Bamboo has fast growth, as culms mature in 3–6 years depending on species, compared to wood, which takes 15 times longer to be harvested. Bamboo can achieve its full height within 4–6 months, with a daily growth rate of 15–18 centimeters (cm). One clump may have 40–50 stems, producing 10–20 culms annually. Bamboo grows faster than any other plant of its size. The rapid growth of bamboo is a significant factor that motivates its utilization (Liese and Köhl, 2015). Bamboo can grow on degraded and marginal lands with other crops in forestry and agroforestry systems; thus, there is no land competition. Bamboo can be harvested yearly without removing the clump for the next 30–50 years, while other biomass requires replanting after harvesting (Sharma *et al.,* 2018). Bamboo is recognized globally due to its ecological, economic, and social benefits. In 2015, Indonesia had

160 bamboo species from 22 genera that covered approximately 2.1 million hectares of land. As a tropical country, Indonesia grows bamboo that belongs to the sympodial tribe, whereas bamboo grown in temperate climates belongs to the monopodial tribe (Liese and Köhl, 2015). In Indonesia, bamboo biomass has traditionally been utilized as a source of firewood for generating heat in households, primarily for cooking and boiling water (Sharma *et al.,* 2018). Sympodial is a type of bamboo that grows in a clumping or spreading manner, producing multiple culms from a single rhizome and forming clusters of culms. This bamboo has sympodial rhizomes, which are horizontal underground stems that grow parallel to the ground and give rise to new culms (Luo *et al.,* 2019). *Gigantochloa pseudoarundinacea* is one of the endemic bamboos of Indonesia from the genera *Gigantochloa*, which is mostly found in Java and Sumatera Island. *G. pseudoarundinacea is* mostly used in the bamboo industry with other species of bamboo, such as *Dendrocalamus asper*, *Bambusa blumeana*, and *Schizostachyum brachycladum* (Maulana *et al.,* 2021). A previous study reported that bamboo's fuel properties have low ash content, high volatile matter, fixed carbon, and calorific value (Park *et al.,* 2020). Bamboo is considered a sustainable and renewable energy resource due to its efficient fuel properties and rapid growth rate. Using bamboo biomass for co-firing with coal is a promising approach for utilizing biomass in energy production. This method can potentially enhance combustion efficiency and reduce the emissions of pollutants and greenhouse gases compared to coal combustion alone (Xiang *et al.,* 2020). Raw biomass presents challenges due to its low density, high moisture content, nonuniform size, hydrophilic nature, and difficulties in transportation, storage, and combustion due to its nonuniform size and longer residence time (Sher *et al.,* 2020). Therefore, raw biomass is inefficient as a renewable energy source (Iftikhar *et al.,* 2019), requiring additional procedures to improve efficiency. Biomass can serve as a reliable and environmentally friendly energy source by using advanced technologies to convert it into solid, liquid, and gaseous states (Chen *et al.,* 2015). Densification is known to increase the quality of biomass with relatively low energy into a solid form (pellets or briquettes). Pelletization produces pellets through a thermomechanical technique to increase the bulk density of solid matter such as wood, bamboo, or sawdust containing lignin and cellulose (García *et al.,* 2019; Solihat *et al.,* 2021). Biomass pellets can be utilized for small-scale and industrial heating applications, combined heat and power (CHP), co-firing, and residential heating applications (Manouchehrinejad and Mani, 2018). They can also be used for animal bedding because biomass pellets have hydrophilic properties (Saputra *et al.,* 2022); they can adsorb animal urination well. The pelletization process increases the density of biomass. Liu *et al.* (2013) discovered that the densification process during pelletization resulted in an increase in the density and energy concentration per unit volume of bamboo pellets. This improvement in density and energy concentration turns bamboo pellets into a more efficient source of bioenergy. Bamboo pellets have a higher energy content compared to other biomass materials, such as rice straw and pine (Liu *et al.,* 2013; 2014), providing efficient energy production. However, their bioenergetic properties are relatively lower than those of coal. Bamboo pellets are fibrous, hydrophilic, and prone to attack by fungi during long-term storage. To resolve this issue, thermal treatment with low oxygen can produce high-energy pellets. Torrefaction refers to a gentle thermal treatment conducted at atmospheric pressure with a temperature between 200-300 degrees Celsius (°C) at a particular time in an inert or low oxygen content. Other names for torrefaction include roasting, mild pyrolysis, wood cooking, and high-temperature drying (Hidayat *et al.,* 2021). Torrefaction affects the physical, chemical, mechanical, and bioenergetic properties of biomass, thereby improving its economic value (Chen *et al.,* 2015). The integration of pelletization and torrefaction produces biomass pellets with a darker appearance, generally referred to as black pellets (García *et al.,* 2019), that have better quality than raw pellets (Nunes *et al.,* 2014). Previous research found that torrefaction at high temperatures of 250–350°C increased the calorific value of soybean straw and pinewood sawdust pellets. The hydrophobicity of the pellets was observed to be higher than that of the raw pellets (Zhang *et al.,* 2020). Different types of reactors are currently employed for biomass torrefaction. Fixed-bed reactors are commonly employed for laboratory-scale torrefaction processes. Such reactors are utilized to study the influence of process conditions

on the properties of the sample, and they are easier to use for biomass torrefaction than other reactors (Ribeiro *et al.,* 2018). Because this is a laboratory-scale reactor, only a small number of torrefied pellets can be produced. The rotary kiln reactor is commonly used in pilot plant projects due to its larger capacity. However, its power efficiency is compromised, as the rotation of the kiln requires additional energy consumption. This reactor has limitations in scaling up due to its inability to accommodate a wide range of biomass sizes (Mei *et al.,* 2015). One of the current developments in torrefaction technology is the fixed counter-flow multi-baffle (Fixed COMB) reactor developed by the Korea Institute of Energy Research (KIER) at the University of Lampung, Indonesia. The reactor uses the principle of heating raw material with hot air blowing at a certain flow rate and time (Iryani *et al.,* 2019). The Fixed COMB reactor offers several advantages for torrefaction biomass, specifically pellets. These benefits include a low gas-to-solid ratio (G/S), a short residence time of 3–5 minutes, a constant temperature difference (driving force) along the column, and the reactor's simplicity, flexibility, and mobility. This reactor is designed for pilot plant production, with a processing capacity of 20 kilograms per hour (kg/h) of biomass (Hidayat *et al.,* 2020). The Fixed COMB reactor has the potential to enhance mass production efficiency at an industrial scale, surpassing the capabilities of conventional furnaces. This development is attributed to the direct heating technology in the Fixed COMB reactor, which facilitates uniform heat distribution throughout the material. The concept of vortex flow is applied to achieve uniform heat distribution across the production area. This advantage is significant, as it reduces the risk of product nonuniformity caused by uneven heating, a common occurrence in conventional methods, such as furnaces (Hidayat *et al.,* 2021). The Fixed COMB reactor enhances heat efficiency and distribution and increases product yield. Efficiency is crucial on a commercial scale, as substantial production quantities are necessary to meet demand (Iryani *et al.,* 2019). *G. pseudoarundinacea* is mostly used in the bamboo industry (Maulana *et al.,* 2021) and has a high calorific value compared to other types of biomasses (Park *et al.,* 2020). Thus, *G. pseudoarundinacea* has potential as a bioenergy source. The study of *G. pseudoarundinacea* as torrefied pellets is still limited. Prior research has focused only on determining the physical characteristics of torrefied *G. pseudoarundinacea* pellets, including moisture content, density, water resistance, and water adsorption (Pah *et al.,* 2021). Presently, no study has been conducted on the characteristics of torrefied *G. pseudoarundinacea* pellets as a form of solid fuel. This study aimed to examine the characteristics of torrefied *G. pseudoarundinacea* pellets using a Fixed COMB reactor, a recent advancement in torrefaction technology. This study was conducted in the forest products workshop in the Integrated Field Laboratory, Faculty of Agriculture, University of Lampung, Indonesia, from 2022–2023.

## MATERIALS AND METHODS

The *G. pseudoarundinacea* bamboo was collected when it was between the ages of three and four years old in Ciawi, located in the Bogor Regency of West Java, Indonesia (latitude 6° 40' 49.3" and longitude 106° 49' 49.6"). Bamboo pellets were produced using a pellet mill with a capacity of one ton of material per hour for processing. Before torrefaction, the bamboo pellets were passed through a strainer and sieved to remove any remaining dust and pellet powder. Afterward, the pellets were categorized into uniform groups based on size, with each measuring 3–4 cm in length. After that, the pellets were dried in an oven for 24 hours at 100°C to evaporate moisture. All pellet samples should have uniform moisture content before torrefaction (Fig. 1). Table 1 displays the characteristics of the unprocessed pellets.

### *Torrefaction process using Fixed COMB reactor*

Torrefaction was performed with a pilot plant Fixed COMB (Fig. 2) reactor developed by KIER. The rector featured a column with baffles that retained the pellets while hot gas flowed through the column, and it used liquefied petroleum gas (LPG) as the fuel (Fig. 2a). Torrefaction is a thermal process conducted at atmospheric pressure, with temperatures ranging from 200–300°C. According to the preliminary research conducted by Pah *et al.* (2021) and Saputra *et al.* (2022), optimal torrefaction results can be attained at a temperature of 280°C, with a residence time of 40–50 minutes. This study conducted torrefaction at 280°C, with a residence time of 3–5 minutes and three cycles, to imitate the preliminary research and compare the results of each cycle. The gas flow rate

Fig. 1: The process of producing bamboo pellets: (a) Raw materials used; (b) The process of removing the outer and inner skin layers of the bamboo; (c) The production process of transforming the bamboo into its powdered form; (d) Drying the bamboo powder; (e) Producing pellets using the pellet mill; (f) Cooling and conditioning process after pelletization.

Table 1: Proximate and ultimate properties of raw *G. pseudoarundinacea* pellets

| Proximate | |
|---|---|
| Volatile matter weight percent dry basis (wt% db.) | 92.40 |
| Ash content wt% db. | 1.33 |
| Fixed carbon wt% db. | 6.27 |
| Ultimate | |
| Carbon (C) | 47.08 |
| Nitrogen (N) | 0.41 |
| Hydrogen (H) | 6.33 |
| Oxygen difference (O diff) | 46.18 |
| Ratio of O atoms to C atoms in a molecule (O/C) | 0.98 |
| Ratio of H atoms to C atoms in a molecule (H/C) | 0.13 |

(column pressure) was 4.25 cubic centimeters per minute (cm$^3$/min), and the temperature difference at the column bottom (T1) and the column top (T2) was plus or minus (±) 50°C (Fig. 2b). The pellet entered the column via the feeder and was torrefied by hot gas from the induced draft fan (ID fan), which blew the air across the combustor and flowed the hot gas from the bottom. Torrefied pellets were collected at the bottom of the column and counted as the first cycle (C1). Torrefaction was conducted in three cycles to determine the characteristics of each cycle. The second cycle (C2) used torrefied pellets from the first cycle, and the third cycle (C3) used torrefied pellets from the second cycle.

### *Thermogravimetric (TGA) analysis*

TGA is a quantitative analytical technique used to inspect the thermal degradation act of *G. pseudoarundinacea* pellets based on the American Society for Testing Materials (ASTM) E1641-16 standard. A thermogravimetric analyzer was used to analyze the raw pellets. A one-gram (g) sample was

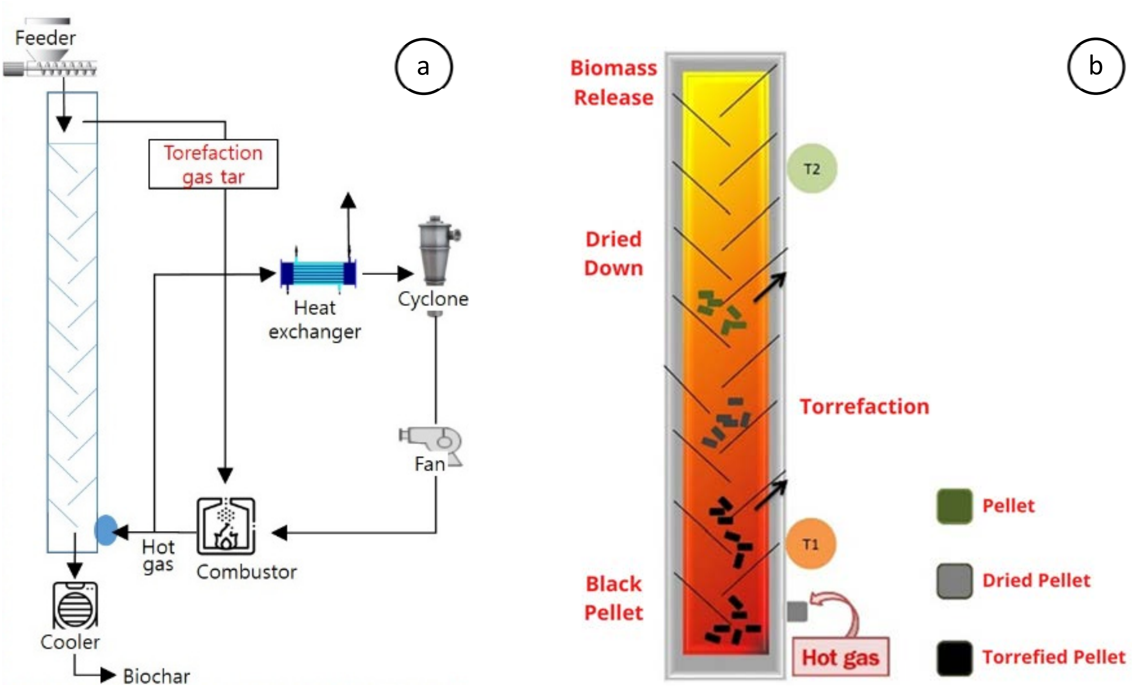

Fig. 2: (a) Fixed COMB reactor schematic; (b) Column condition during the torrefaction process

used and heated in an inert atmosphere from 30–900°C.

*Physical properties*

A colorimeter with a *Commission Internationale de l´Eclairage* (CIE-Lab) system was used to conduct color change tests before and after torrefaction. The overall color change ($\Delta E^*$) was calculated using Eq. 1 (Valverde and Moya, 2014).

$$\Delta E^* = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2} \quad (1)$$

In this context, the variables $\Delta E^*$, $\Delta L^*$, $\Delta a^*$, and $\Delta b^*$ represent the overall color change, change in lightness, change in red/green chromaticity, and change in yellow/blue chromaticity, respectively. The classification of color changes according to Valverde and Moya (2014) is shown in Table 2.

Density is the measure of a sample's weight-to-volume ratio. Obtaining this measurement entailed determining the weight and volume of the samples in both air-dry and oven-dry conditions. In accordance with the Indonesian National Standard (SNI) 8021-2014, density (D) was determined using Eq. 2 (Saputra *et al.,* 2022).

$$D = \frac{W}{V} \quad (2)$$

In this equation, W represents the weight of the pellet (g), and v represents the volume of the pellet in cubic centimeters (cm$^3$). Moisture content determination was used primarily to compare the weight loss resulting from heat treatment with the initial weight of the samples. The moisture content of the sample was determined by subjecting it to a 24-hour drying process in an oven at a temperature of 100°C. The sample's weight was measured prior to and following the drying procedure. In accordance with SNI 01-1506, the moisture content (MC) was determined using Eq. 3 (Saputra *et al.,* 2022).

$$MC = \frac{(W_1 - W_0)}{W_0} \times 100\% \quad (3)$$

Where, $W_1$ is the initial weight (g), and $W_0$ is the oven-dried weight (g).

*Mechanical properties*

Compressive strength tests were conducted using a universal testing machine. The diameters of the

Table 2: Classification of color changes

| No. | Classification value | Description |
|---|---|---|
| 1 | 0.0 Is less than (<) $\Delta E^*$ Is less than or equal to (≤) 0.5 | Negligible |
| 2 | $0.5 < \Delta E^* \leq 1.5$ | Slightly Perceivable |
| 3 | $1.5 < \Delta E^* \leq 3$ | Noticeable |
| 4 | $3 < \Delta E^* \leq 6$ | Appreciable |
| 5 | $6 < \Delta E^* \leq 12$ | Very Appreciable |
| 6 | $\Delta E^*$ Is greater than (>) 12 | Totally Changed |

torrefied pellets were measured, and their tips were flattened to ensure stability during machine operation. The pellets were compressed using the machine until they fractured or developed cracks. Subsequently, the machine ceased operation and displayed the graphical representation along with the highest recorded value during the test. The compressive strength (CS) value was determined using Eq. 4 (Saputra *et al.,* 2022).

$$\mathrm{CS} = \frac{\mathrm{P}}{\mathrm{A}} \tag{4}$$

Where, P is the maximum load (N), and A is the surface area ($\mathrm{mm}^2$).

*Bioenergetic properties*

Calorific value is the heat generated when one unit mass of fuel undergoes complete combustion with water in steam form, and it is quantified in megajoules per kilogram (MJ/kg). A bomb calorimeter was used to conduct the calorific test following the SNI 8675-2018 standard.

*Proximate analysis*

A bomb calorimeter was used to conduct a proximate analysis of volatile matter, fixed carbon, and ash content according to the SNI 8675-2018 standard. Volatile matter denotes the weight percentage lost during the heating of a substance in the absence of external air. The analysis of volatile matter adhered to the SNI 8675-2018 standard and was calculated using Eq. 5 (Hidayat *et al.,* 2017).

$$\text{Volatile matter}(\%) = \frac{\text{Sample Weight Loss}(\mathrm{g})}{\text{Dry Sample Weight}(\mathrm{g})} \times 100\% \tag{5}$$

Fixed carbon is the residual part of a sample that remains after removing moisture content, ash content, and volatile matter fraction. SNI 8675-2018 provided the basis for performing the fixed carbon analysis, and Eq. 6 (Hidayat *et al.,* 2017) was utilized to compute the fixed carbon.

$$\text{Fixed carbon} = 100\% - (\text{Ash content} - \text{Volatile matter}) \tag{6}$$

Ash content is the residual mineral matter remaining after combustion that does not evaporate. The ash content test analysis followed the guidelines outlined in the SNI 8675-2018 standard, and Eq. 7 (Hidayat *et al.,* 2017) was used to determine the ash content.

$$\%\text{Ash Content} = \frac{\text{Ash Weight}(\mathrm{g})}{\text{Dry Sample Weight}(\mathrm{g})} \times 100\% \tag{7}$$

*Ultimate analysis*

An elemental analyzer was used to conduct the ultimate analysis of the bamboo pellets. The analyzer was calibrated using five tin capsules containing L-cystine sample. A tin capsule contained powdered bamboo pellet sample weighing 0.1 milligram (mg). The experiment involved subjecting the sample to a temperature of 980°C while maintaining a continuous supply of helium gas mixed with oxygen.

*Fourier-transform infrared (FTIR) analysis*

FTIR analysis was conducted using Fourier-transform infrared spectroscopy with the potassium bromide (KBr) technique. FTIR analysis was conducted to evaluate biomass quality and to examine alterations in functional groups (Samimi and Shahriari-Moghadam, 2023). The FTIR spectrum utilizes infrared radiation to pass through the sample gap, where the energy delivered to the sample is regulated by the slit (Ehzari *et al.,* 2022). The sample absorbs specific wavelengths of infrared light and allows others to pass through its surface. The infrared rays are transmitted to the detector, and the resulting signal is then sent to the computer for measurement.

*Chemical properties*

The composition of the torrefied products was determined following the method adapted from Datta (1981) with some modifications. Prior to analyzing the composition of the torrefied product, an extraction process was conducted using hot water and an extractor to determine the extractive content. The extractive sample was dried and mixed with 1.5 milliliters (mL) of 72 percent by weight (wt%) sulfuric acid ($H_2SO_4$) at 30°C for 1 hour. The treated sample was hydrolyzed in an autoclave at 121°C for 1 hour after adding 42 mL of water. The hydrolyzed sample underwent cooling, filtration, and multiple washes using hot water. The residue obtained was identified as Klason lignin, which refers to the acid-insoluble solid residue. It was subsequently dried at a temperature of 105°C overnight.

## RESULTS AND DISCUSSION

### *Thermogravimetric (TG) and derivative thermogravimetric (DTG) analyses*

TG and DTG (Fig. 3) showed that the torrefaction with a temperature of 285°C resulted in a 78.5% production yield. Through thermal degradation, the product decreased by 9.2%, 55.1%, and 38% from 30–900°C, respectively. As shown in the graph's diver-time line, the two peaks were at temperatures of 50.5°C and 350°C. It was suspected that the peak at 50–100°C was moisture degradation, as reported in a previous study (Rani *et al.,* 2021), and then the degradation peak at 350°C was a biopolymer. Bamboo mainly consists of cellulose, hemicellulose, and lignin, with different responses at specific temperatures (Jagnade *et al.,* 2022). Hemicelluloses undergo decomposition within the temperature range of 200–380°C, whereas cellulose and lignin decompose within the temperature ranges of 250–380°C and 180–900°C, respectively (Chen *et al.,* 2015).

As previously mentioned, weight loss was divided into three phases in agreement with the literature (Burhenne *et al.,* 2013). The initial phase of weight loss was attributed to the removal of moisture and bound water, which is known as the dehydration phase. The next phase, referred to as active pyrolysis, leads to rapid weight loss. The combustion of hemicellulose and cellulose components corresponds to this rapid weight loss (Zakikhani *et al.,* 2015). Lignin decomposition occurred gradually within a broad temperature range of 180–900°C. The reaction exhibited a minor order, leading to a gradual reduction in weight until it reached zero in the final stage. This final stage was identified as passive pyrolysis (Chen *et al.,* 2015).

### *Effect of torrefaction using a Fixed COMB reactor on color change*

The results showed a distinction between each

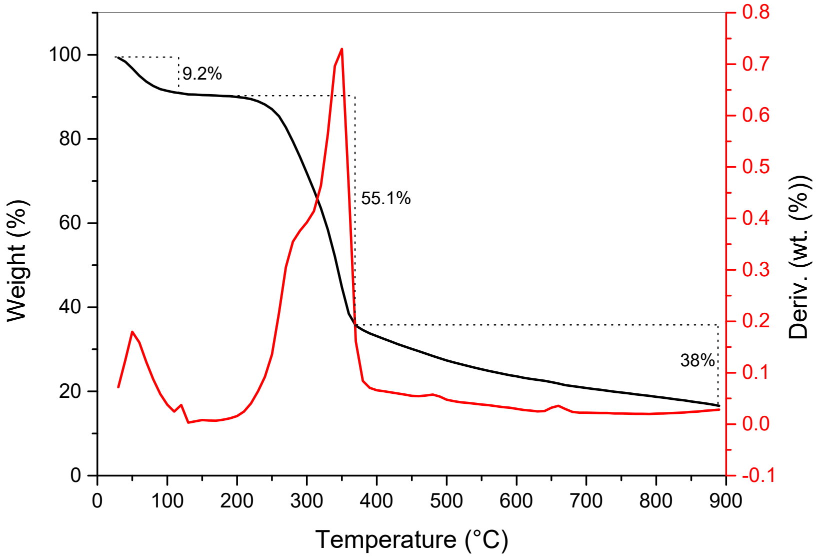

Fig. 3: TG and DTG curves of bamboo pellets.

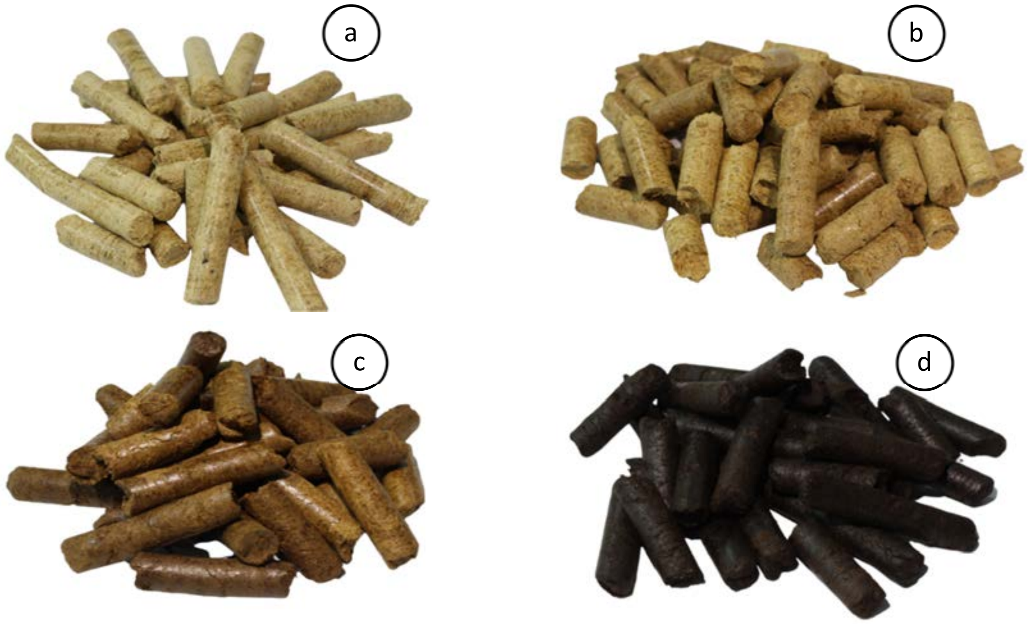

Fig. 4: The visual appearance of the bamboo pellets (a: control, b: C1, c: C2, d: C3)

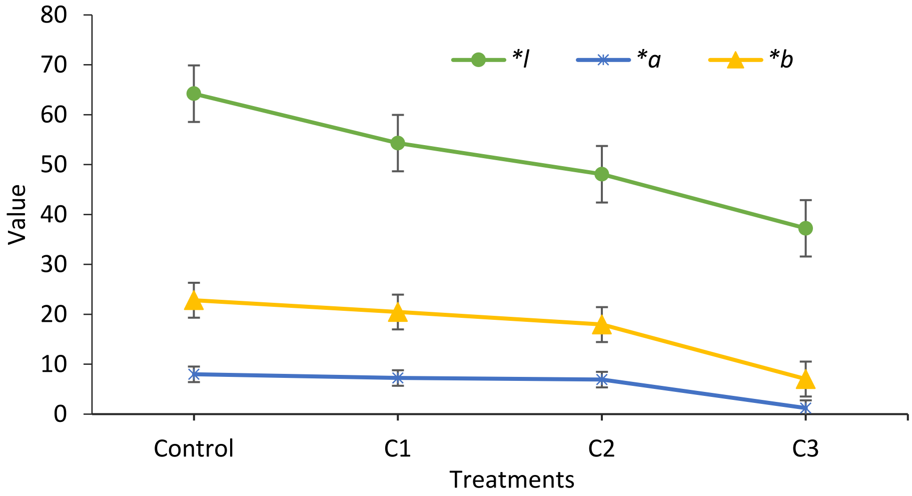

Fig. 5: Effect of the torrefaction cycle process on the change in *L**, *a**, and *b** in *G. pseudoarundinacea* bamboo pellets

treatment in terms of color change (Fig. 4). The treatment quickly produced a genuine empirical color change in the appearance of each pellet. The raw pellet/control (Fig. 4a), without any heat treatment, had the lightest brown color compared to the treated pallets. Only during C3 did the pellets turn into black pellets (Fig. 4d); in C1 (Fig. 4b) and C2 (Fig. 4c), the torrefaction made the pellets darker but not black. Based on the *CIE-Lab* system (Fig. 5), all parameters (*L**, *a**, and *b**) were decreased to a lower score along with the torrefaction cycle added. The trends in the **a* and **b* parameters resulted in a similar pattern in which C1 and C2 underwent plateau conditions and then dropped on the latest treatment. Score-wise (Table. 3), the *L**, *a**, and *b** parameters show that C3 had the lowest score among treatments by 37.24,

Table 3: Effect of the torrefaction cycle process on the color change of *G. pseudoarundinacea* bamboo pellets

| Treatment | Parameters | | | | |
|---|---|---|---|---|---|
| | *L** | *a** | *b** | *ΔE** | *ΔE** Level |
| Control | 64.22 | 7.26 | 22.84 | - | - |
| C1 | 54.32 | 6.94 | 20.48 | 58 | Totally Changed |
| C2 | 48.08 | 5.82 | 17.96 | 52 | Totally Changed |
| C3 | 37.24 | 1.22 | 7.04 | 38 | Totally Changed |

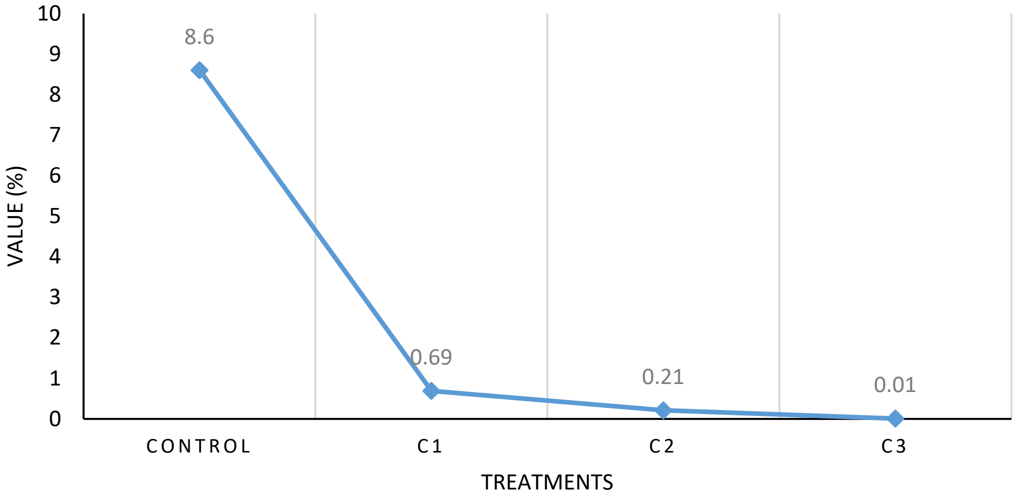

Fig. 6: Effect of the torrefaction cycle process on the change in moisture content in *G. pseudoarundinacea* bamboo pellets.

1.22, and 7.04, respectively, indicating that the C3 pellets had the darkest color compared to the other treatments and the control. The color change levels for C1, C2, and C3, based on the *ΔE**, was categorized in total change by 58, 52, and 38, respectively. The results demonstrate a similar pattern to Park *et al.* (2020), who found that the color of the biomass pellets became darker at higher temperatures and longer residence times. Consistent with the findings of Via *et al.* (2013), the color of torrefied biomass was observed to transition from a darker brown shade at lower temperatures to nearly black at 300°C. Torrefaction induces a color alteration in biomass through devolatilization and carbonization processes, resulting in a darker or blackened appearance, which varies depending on the level of torrefaction severity. The degradation of hemicellulose and the movement of the extractive component can decrease lightness (*L**), and the degradation may accelerate as the treatment temperature rises (Chen *et al.,* 2015). Hidayat *et al.* (2015) reported that a temperature range of 180–200°C substantially impacted the color change of biomass during heat treatment. According to Huang *et al.* (2020), the color change of torrefied biomass can be used as an indicator for predicting the quality of torrefied products. This is because the color parameter of torrefied biomass is strongly correlated with weight loss, volatile matter, and a higher heating value (HHV).

### *Moisture content*

Torrefaction conducted with a Fixed COMB reactor during C3 treatment achieved a significant reduction in moisture content, reaching a level of 99.8%. The addition of the torrefaction cycle (Fig. 6) resulted in a decrease in moisture content consistent with the existing literature, which shows a decrease in moisture content with longer residence time. At the maximum temperature and residence time, the macro-TG reactor achieved a moisture content reduction of 76% (Chaves *et al.,* 2021), whereas the atmospheric pressure steam reactor reduced moisture content to 81% (Tu *et al.,* 2022). The results indicate that the Fixed COMB reactor exhibited the lowest moisture content compared to other reactors. The liberation of unbound water from the torrefied biomass was a result of the elevated temperature and prolonged duration, which coincided with a reduction in moisture content (Peng *et al.,* 2013). Low moisture content is beneficial in degrading the ability of fungi to grow during biomass storage, and it also reduces transportation costs. Reducing moisture content can mitigate storage problems, such as off-gassing and self-heating, and facilitate long-term storage (Pah *et al.,* 2021).

### *Physical, mechanical, and bioenergetic properties*

The torrefaction process improves the calorific value throughout the added cycle. The HHV of C3 reached 21.13 MJ/kg, which increased by 18.6% from the control pellets' HHV. The density of the control pellets decreased by 40.8% after C3 treatment, dropping from 1.38 grams per cubic centimeter (g/cm$^3$) to 0.81 g/cm$^3$. This indicates an improvement compared to the torrefaction using the macro-TG reactor at maximum temperature and residence time, which increased the HHV only 2.7% and decreased the density by 8% (Chaves *et al.,* 2021). The decrease in density of torrefied pellets is attributed to the evaporation of moisture, extractives, and partial degradation of hemicellulose during heat exposure via torrefaction (Yang et al., 2007). Furthermore, the compressive strength of the control pellet was 2.46 Newtons per square millimeter (N/mm$^2$) and increased to 3.28 N/mm$^2$ in C1; however, it decreased in C2 and C3. While C1 represents the critical temperature at which the strength remains unaffected, exceeding this cycle can lead to decreased strength (Saputra *et al.,* 2022). The results showed an association between the density and compressive strength of biomass pellets. Denser biomass pellets typically exhibit greater compressive strength and vice versa (Saha *et al.,* 2022). Based on solid fuel utilization, C3 was a preferable pellet compared to the other treatments, producing a higher calorific value and lower density and compressive strength (Table 4). Torrefaction at high temperatures enhances the energy density and fuel characteristics of torrefied biomass, making it more suited for solid fuels (Pah *et al.,* 2021). Torrefaction temperature and residence time impact the grindability of torrefied biomass. Increasing the temperature and duration of residence will improve grindability. Water evaporation during torrefaction decreases the density of torrefied biomass, making it more brittle but increasing its HHV (Yu *et al.,* 2019). Hemicellulose degradation during heat treatment weakens the hydrogen bonding between particles and reduces cohesiveness inside the biomass, which affects the lowering of compressive strength. As the torrefaction temperature rises, the rate of degradation, primarily in hemicellulose, and the decreased interparticle hydrogen bonding increase. During the torrefaction process, the relative presence of oxygen and hydrogen is reduced compared to carbon, resulting in an increase in the calorific value of biomass that has undergone torrefaction (Peng *et al.,* 2013).

### *Proximate analysis*

A Fixed COMB reactor could upgrade biomass characteristics, making them more suitable for solid fuel utilization. C3 treatment could increase the fixed carbon by 14.52 wt% db. (Table 5). Increasing fixed carbon content can improve the efficiency of biomass combustion. Nevertheless, the volatile matter and ash content unavoidably accrued when the torrefaction cycle was added. Volatile matter and ash content for C were 89.17 and 1.81, respectively, which means that they increased by 6.18% and 26.5%. Using a macro-TG reactor, Chaves *et al.* (2021) observed the characterization of torrefied *Phyllostachys aurea* bamboo pellets. They stated that the ash content and fixed carbon increased by 1.02% and 17.35%, respectively, while the volatile matter decreased to 81.64%. Saha *et al.* (2022) reported that the torrefaction process of *Gigantochloa scortechinii* bamboo chips in a vertical mass flow reactor resulted in a 39% increase in fixed carbon content and a 58%

Table 4: Effect of the torrefaction cycle process on the physical, mechanical, and bioenergetic properties of *G. pseudoarundinacea* bamboo pellets

| Parameters | Treatments | | | |
|---|---|---|---|---|
| | Control | C1 | C2 | C3 |
| Calorific value (MJ/kg) | 17.81 | 18.14 | 19.23 | 21.13 |
| Density (g/cm$^3$) | 1.38 | 1.24 | 1.19 | 0.81 |
| Compressive strength (N/mm$^2$) | 2.46 | 3.28 | 1.84 | 1.74 |

Table 5: Effect of the torrefaction cycle process on the proximate of *G. pseudoarundinacea* bamboo pellets

| Parameters | Treatments | | |
|---|---|---|---|
| | C1 | C2 | C3 |
| Volatile Matter wt.% db. | 89.58 | 86.25 | 83.67 |
| Ash Content wt.% db. | 1.13 | 1.41 | 1.81 |
| Fixed Carbon wt.% db. | 9.29 | 12.34 | 14.52 |

Table 6: Effect of the torrefaction cycle process on the ultimate *G. pseudoarundinacea* bamboo pellets

| Parameters | Treatments | | |
|---|---|---|---|
| | C1 | C2 | C3 |
| C | 47.46 | 48.99 | 52.86 |
| N | 0.35 | 0.31 | 0.29 |
| H | 6.23 | 5.89 | 5.7 |
| O (diff) | 45.96 | 44.81 | 41.15 |
| O/C | 0.97 | 0.91 | 0.78 |
| H/C | 0.13 | 0.12 | 0.11 |

decrease in volatile matter content with an increasing torrefaction temperature. These findings align with prior studies on woody biomass (Colin *et al.,* 2017). The ash content in each cycle is relatively low, ranging from 1.13–1.81%, below the maximum limit specified in SNI 8675-2018 of 5%. Increasing the torrefaction temperature of bamboo pellets resulted in higher fixed carbon, increasing their calorific value, which is in line with increased ash content, making the pellets more difficult to burn and resulting in a larger residue. However, a slight increase in ash content did not significantly reduce the calorific value. The high carbon value and low ash content of bamboo pellets directly impact calorific value, improving the quality of solid fuels (Niu *et al.,* 2019).

### *Ultimate analysis*

The torrefaction with the Fixed COMB reactor used limited oxygen to prevent combustion, improving the C content in the product (pellet). The C3, with a longer residence time than the other treatments, had the highest C content of 52.86% (Table 6), which is expected for solid fuel. The Fixed COMB reactor increased the C content by 11%. This result shows a higher C content than torrefaction using a slot-spouted rectangular bed reactor at the highest temperature and residence time (Wang *et al.,* 2019). However, under the same conditions, it was still lower than when using a moving bed reactor (Kongto *et al.,* 2021). A high C content is beneficial for solid fuel because it corresponds to the highest HHV (Niu *et al.,* 2019), as shown in Fig. 6. Formerly, the concentrations of N, H, and O declined by 0.29%, 5.7%, and 41.15%, respectively, after C3 was performed. Less N content in solid fuel will decrease the induced heavy emission of nitrogen oxide ($NO_x$), which is toxic to the environment, during combustion; simultaneously, reducing the concentrations of H and O can effectively mitigate the production of water vapor and smoke during combustion (Matali *et al.,* 2016) and increase hydrophobic properties (Saputra *et al.,* 2022).

The Van Krevelen diagram indicates that the concentration ratio of C, H, and O determines the quality of solid fuel for combustion. A lower concentration ratio indicates a higher quality of solid fuels. This is supported by the observation that torrefied biomass exhibits properties similar to lignite and coal due to chemical changes caused by heat treatment (Poudel *et al.,* 2018). The diagram in Fig. 6 shows that as a cycle was added, the value lowered. The C3 is the lowest value among the treatments, and the distance is promptly shown, which indicates better solid fuel quality. This follows the same trend in the torrefaction of various biomasses, indicating a preference for coal at temperatures over 250°C. The comparison of the cycle depicted in Fig. 6 reveals that the torrefaction decomposition process involves significant dehydration. This is evident from the observed changes in the O/C and H/C atomic ratios of the biomass, which align with dehydration pathways. The decrease in hydrogen and oxygen content during the torrefaction process, which leads to increased HHV in torrefied bamboo, is primarily attributed to hydrogen and deoxygenation reactions (Fig. 7; Li *et al.,* 2015). A torrefied biomass with low O/C and H/C ratios is a suitable solid fuel due to its reduced emissions of smoke, water vapor, and energy loss during combustion (Nunes *et al.,* 2014).

*FTIR analysis*

FTIR analysis was performed to determine the chemical composition of the biomass and to observe changes in the functional groups (Samimi, 2024) (Fig. 8). The peak range at 3,600–3,200/cm, shown in Table 7 and corresponding to the hydroxyl group (OH), decreased as cycles were added. The functional groups of the methyl group (CH) were found in the peak range of 3,000–2,700/cm. The lignin structure or carbon-carbon double bond (C=C) group was found at a peak of 1,800–1,500/cm. The carbon-oxygen single bond (C-O) group was found at a peak range of 1,200–900/cm; it decreased with increasing temperatures. The findings of this study are in

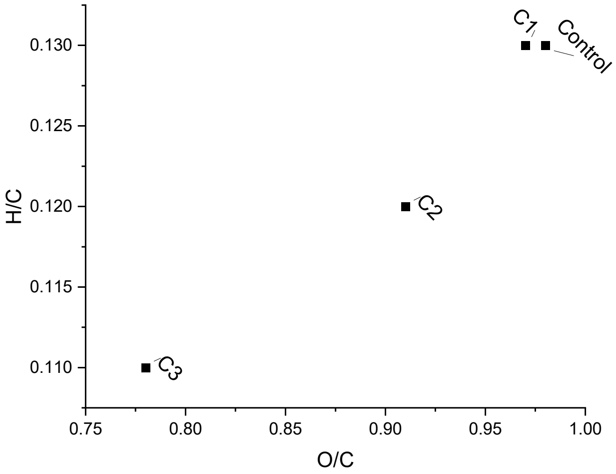

Fig. 7: Van Krevelen diagram of the torrefaction of *G. pseudoarundinacea.*

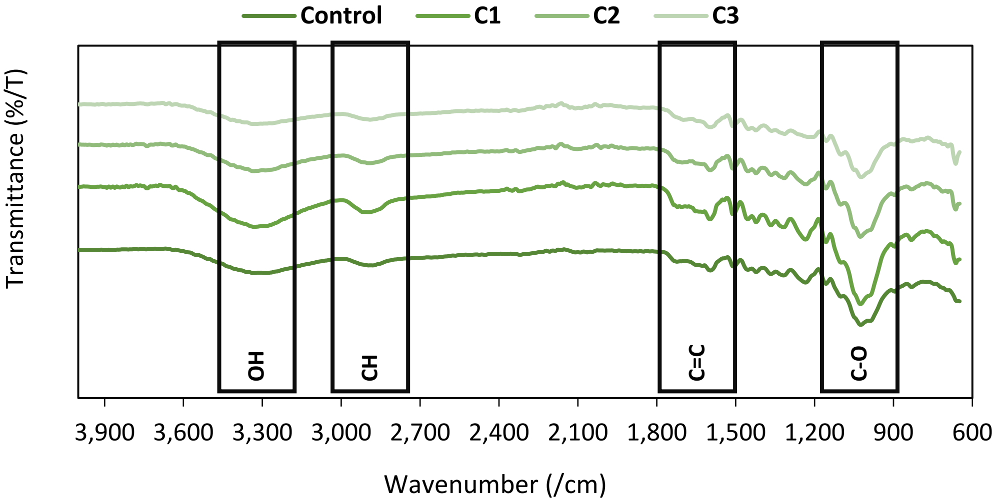

Fig. 8: FTIR analysis of *G. pseudoarundinacea* bamboo pellets before and after torrefaction at various cycles.

Table 7: Compound type for FTIR analysis of *G. pseudoarundinacea* bamboo pellets

| Elemental bonds | Peak range (/cm) | Compound type |
|---|---|---|
| OH | 3,600–3,200 | Acid, methanol |
| CH | 3,000–2,700 | Alkane |
| C=C | 1,800–1,500 | Benzene |
| C-O | 1,200–900 | Ethanol |

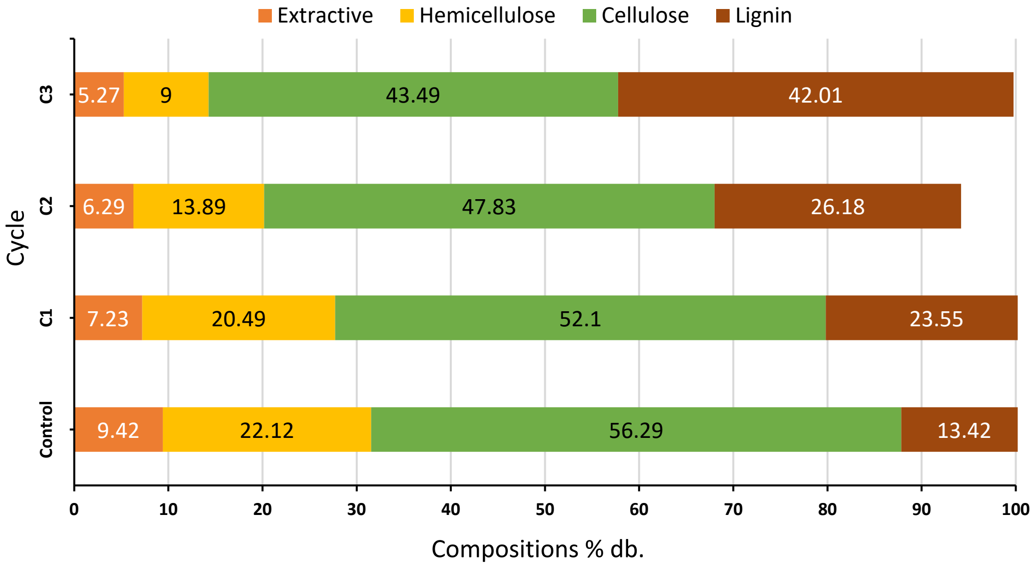

Fig. 9: Chemical compositions change due to the torrefaction cycle.

good agreement with those of Chen *et al.* (2015) and other studies of soybean straw pellets and pine wood pellets (Cao *et al.,* 2021) and rice husk, groundnut shell, and corn cob (Garba *et al.,* 2018). The high temperature during torrefaction triggered a biopolymer breakdown, resulting in a distinct peak between raw and torrefied pellets that declined as the cycle number increased (Manatura, 2020). Chen *et al.* (2015) clarified that torrefaction significantly affects the decomposition of carbohydrates, proteins, and lipids. Higher temperatures encourage the degradation of hemicellulose, cellulose, and lignin by adding cycles and changes in functional groups that are becoming larger, as illustrated by the steeper absorption peak (Fig. 8).

*Chemical analysis*

Fig. 9 shows that the extractive and hemicellulose fractions are more susceptible to degradation through thermal treatment than cellulose and lignin. Cellulose undergoes partial decomposition in C1. The analytical findings indicate an increase in lignin content following torrefaction. Torrefaction can be achieved rapidly using a Fixed COMB reactor, with a residence time as short as 3 minutes. The impact of temperature on biomass degradation was more significant than residence time. As a result, the C1 process caused only minimal chemical changes due to its short torrefaction duration. The chemical compositions decreased mainly due to hemicellulose degradation and extractive loss after water evaporation in addition to the torrefaction process (Shoulaifar *et al.,* 2014). C3 treatment reduced hemicellulose by 59.31%; however, extractive and cellulose treatments reduced it by only 44.05% and 22.73%, respectively. This is because hemicellulose is substantially more thermally unstable than other compositions (Shen *et al.,* 2010). At C3, the lignin content increased by 313%, while the other components were reduced. This is attributed to the wide temperature range of lignin, which spans from 180–900°C (Chen *et al.,* 2015). Lignin is retained in the solid product, while the remaining components undergo decomposition. Because lignin has emerged as the predominant energy source in biomass, a high lignin concentration will enhance HHV (Duranay and Akkuş, 2021).

## CONCLUSION

The bamboo pellets' physical, chemical, and thermal properties changed significantly after the addition of the torrefaction cycle. Torrefaction changed the bamboo pellet color, indicating darker and better pellets for solid fuel use. Torrefaction using a Fixed COMB reactor reduced moisture content by 99.8% at C3, indicating the highest moisture decrease of all reactors. Lower moisture content reduced fungal growth and improved biomass storage and transportation. Torrefaction increased the calorific value and physical and mechanical properties. C3 pellets had the highest HHV of 21.62 MJ/kg, 16.6% higher than the raw pellets. Torrefaction decreases density and compressive strength, improving grindability and combustion to make better pellets. The torrefaction cycle increased fixed carbon, volatile matter, and ash. The final analysis showed increased carbon and decreased nitrogen, hydrogen, and oxygen, improving solid fuel quality, energy density, and combustion emissions. FTIR analysis showed torrefaction-induced changes in functional groups and chemical composition, including extractive and hemicellulose degradation and lignin increase. The chemical analysis showed that temperature and residence time degraded hemicellulose and increased lignin concentration in the torrefied pellets. C3 was a preferable pellet among all treatments, achieving the highest calorific value and a low moisture content that improved biomass storage. In conclusion, the Fixed COMB reactor torrefaction process improved *G. pseudoarundinacea* bamboo pellet properties for solid fuel use. This study's findings help understand torrefaction and how to optimize conditions to produce high-quality biomass products. These findings can be used to investigate torrefaction's potential benefits in various industries and energy sectors.

## AUTHOR CONTRIBUTIONS

W. Hidayat defined the study direction's concept, decision, and justification. B.A. Wijaya and B.B. Park performed the data analysis and its interpretation. B. Saputra performed the experiments and drafted the manuscript text. I.T. Rani created the figures, tables, and graphics. S. Kim performed the research methodology. S. Lee was responsible for consultation as well as the analysis of the research findings. J. Yoo performed an analysis of the study findings using instrumental methods. L. Suryanegara and M.A.R. Lubis provided consultations and analyzed the characteristics of the bamboo.

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## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the authors protected against ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

## OPEN ACCESS

## PUBLISHER'S NOTE

## ABBREVIATIONS

| | |
|---|---|
| % | Percent |
| < | Is less than |
| > | Is greater than |
| ± | Plus or minus |
| Δa* | Change in red/green chromaticity |
| Δb* | Change in yellow/blue chromaticity |
| ΔE* | Overall color change |
| ΔL* | Change in lightness |
| ≤ | Is less than or equal to |
| °C | Degree Celsius |
| A | Surface area |
| a* | Red/green chromaticity |
| ASTM | American Society for Testing Materials |
| b* | Yellow/blue chromaticity |
| Bt | Billion ton |
| C | Carbon |
| C=C | Carbon-carbon double bond |
| C1 | First cycle |
| C2 | Second cycle |
| C3 | Third cycle |
| CCS | Carbon capture storage |
| CH | Methyl group |
| CHP | Combined heat and power |
| CIE-Lab | Commission Internationale de l´Eclairage |
| Cm | Centimeter |
| $cm^3$ | Cubic centimeter |
| $cm^3/min$ | Cubic centimeter per minute |
| CMA | Meeting of the Parties to the Paris Agreement |
| C-O | Carbon-oxygen single bond |
| $CO_2$ | Carbon dioxide |
| COMB | Counter-flow multi-baffle |
| CS | Compressive strength |
| D | Density |
| db. | Dry basis |
| DTG | Derivatives thermogravimetric |
| FTIR | Fourier-transform infrared |
| G | Gram |
| $g/cm^3$ | Gram per cubic centimeter |
| G/S | Gas to solid ratio |
| GHG | Greenhouse gas |
| H | Hydrogen |
| H/C | Ratio of hydrogen (H) atoms to carbon (C) atoms in a molecule |
| $H_2SO_4$ | Sulfuric acid |
| HHV | Higher heating value |
| ID Fan | Induced draft fan |
| KBr | Potassium bromide |
| Kg | Kilogram |
| kg/h | Kilogram per hour |
| KIER | Korea Institute of Energy Research |
| L* | Lightness |
| LPG | Liquefied petroleum gas |
| LTS-LCCR | Long-Term Strategy for Low Carbon and Climate Resilience |
| MC | Moisture content |
| Mg | Milligram |
| MJ | Megajoule |
| MJ/kg | Megajoules per kilogram |
| mL | Milliliter |
| $mm^2$ | Millimeter square |
| MPa | Megapascal |
| N | Newton |
| N | Nitrogen |
| $N/mm^2$ | Newton per square millimeter |
| NDC | Nationally determined contributions |
| NOx | Nitrogen oxide |
| O | Oxygen |
| O (diff) | Oxidation (diffusion) |
| O/C | Ratio of oxygen (O) atoms to carbon (C) atoms in a molecule |
| OH | Hydroxyl group |

| | |
|---|---|
| *P* | Maximum test load |
| *SNI* | Standar Nasional Indonesia (Indonesian National Standard) |
| *T1* | Column bottom |
| *T2* | Column top |
| *TG* | Thermogravimetric |
| *TGA* | Thermogravimetric analysis |
| *TWh* | Terawatt-hour |
| *UNFCCC* | United Nations Framework Convention on Climate Change |
| *W* | Weight |
| *wt.%* | Percent by weight |
| *wt.% db.* | Weight percent dry basis |

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**AUTHOR (S) BIOSKETCHES**

**Hidayat, W.,** Ph.D., Associate Professor, Department of Forestry, Faculty of Agriculture, University of Lampung, Jl. Prof. Dr. Ir. Sumantri Brojonegoro No.1, Lampung 35141, Indonesia.

- Email: *wahyu.hidayat@fp.unila.ac.id*
- ORCID: 0000-0002-6015-1623
- Web of Science ResearcherID: F-8410-2017
- Scopus Author ID: 6507549479
- Homepage: https://www.unila.ac.id/

**Wijaya, B.A.**, B.A. Research student, Climate Change Research Division, Korean Institute of Energy Research (KIER), Daejon, 34129, Republic of Korea.

M.Sc. Candidate, Department of Environment and Forest Resources, College of Agriculture and Life Science, Chungnam National University, 99 Daehak-ro, Daejeon, 34134, Republic of Korea.

- Email: *bangun@kier.re.kr*
- ORCID: 0009-0004-6238-1029
- Web of Science ResearcherID: NA
- Scopus Author ID: 57547377200
- Homepage: https://www.kier.re.kr/

**AUTHOR (S) BIOSKETCHES**

**Saputra, B.**, B.A. student, Department of Forestry, Faculty of Agriculture, University of Lampung, Jl. Prof. Dr. Ir. Sumantri Brojonegoro No.1, Lampung 35141, Indonesia.
- Email: *bgs.saputra248@gmail.com*
- ORCID: 0009-0000-4378-1853
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://www.unila.ac.id/

**Rani, I.T.**, B.A. Research student, Climate Change Research Division, Korean Institute of Energy Research (KIER), Daejon, 34129, Republic of Korea. M.Sc. student, Department of Environment and Forest Resources, College of Agriculture and Life Science, Chungnam National University, 99 Daehak-ro, Daejeon, 34134, Republic of Korea.
- Email: *irmathyar@gmail.com*
- ORCID: 0000-0002-3456-0079
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Homepage: https://www.kier.re.kr/

**Kim, S.**, Ph.D., Researcher, Climate Change Research Division, Korean Institute of Energy Research (KIER), Daejon, 34129, Republic of Korea.
- Email: *sdkim@kier.re.kr*
- ORCID: 0000-0002-7746-145X
- Web of Science ResearcherID: NA
- Scopus Author ID: 7601601205
- Homepage: https://www.kier.re.kr/

**Lee, S.**, Ph.D., Researcher, Climate Change Research Division, Korean Institute of Energy Research (KIER), Daejon, 34129, Republic of Korea.
- Email: *lsh3452@kier.re.kr*
- ORCID: 0000-0003-2346-3414
- Web of Science ResearcherID: NA
- Scopus Author ID: 56063656500
- Homepage: https://www.kier.re.kr/

**Yoo, J.**, Ph.D., Researcher, Climate Change Research Division, Korean Institute of Energy Research (KIER), Daejon, 34129, Republic of Korea.
- Email: *jyoo@kier.re.kr*
- ORCID: 0000-0002-4003-8180
- Web of Science ResearcherID: NA
- Scopus Author ID: 56063656500
- Homepage: https://www.kier.re.kr/

**Park, B.B.**, Ph.D., Department of Environment and Forest Resources, College of Agriculture and Life Science, Chungnam National University, 99 Daehak-ro, Daejeon, 34134, Republic of Korea.
- Email: *bbpark@cnu.ac.kr*
- ORCID: 0000-0002-0620-7374
- Web of Science ResearcherID: NA
- Scopus Author ID: 7402834688
- Homepage: https://forestry.cnu.ac.kr/forestry/

**Suryanegara, L.**, Ph.D., Researcher, Research Center for Biomass and Bioproduct, National Research and Innovation Agency (BRIN). Jl. Raya Jakarta-Bogor Km. 46, Cibinong, Bogor, 16911, Indonesia.
- Email: *l_suryanegara@yahoo.co.id*
- ORCID: 0000-0003-0060-0981
- Web of Science ResearcherID: AAS-6738-2020
- Scopus Author ID: 26326619700
- Homepage: https://www.brin.go.id/

**Lubis, M.A.R.**, Ph.D., Researcher, Research Center for Biomass and Bioproduct, National Research and Innovation Agency (BRIN). Jl. Raya Jakarta-Bogor Km. 46, Cibinong, Bogor, 16911, Indonesia.
- Email: *adlylubis89@gmail.com*
- ORCID: 0000-0001-7860-3125
- Web of Science ResearcherID: K-2440-2019
- Scopus Author ID: 57192278476
- Homepage: https://www.brin.go.id/

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