

## Effect of torrefaction temperature and HDPE binder addition on the physicochemical and combustion properties of elephant grass bio pellets

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### Abstract

This study investigates the effect of torrefaction temperature and the addition of HDPE binder on the physical, chemical, and combustion properties of elephant grass (*Pennisetum purpureum*) biopellets. The samples were torrefied at 225°C and 275°C, with an HDPE plastic added at concentrations of 0, 5, 10, 15, and 20%. The results showed that higher torrefaction temperatures substantially reduced the solid yield due to the thermal decomposition of hemicellulose and cellulose, while simultaneously increasing fixed carbon and ash content. Apparent density and drop resistance showed a positive correlation with the addition of HDPE, indicating improved durability and structural integrity of the pellets. The hydrophobicity test revealed longer water penetration times with increasing HDPE content, demonstrating enhanced moisture resistance, although a slight decline was observed at 275°C due to polymer degradation. During combustion, pellets torrefied at 275°C exhibited a faster temperature rise and more stable mass reduction compared to those processed at 225°C, reflecting better combustion efficiency and heat transfer performance. The relationship between proximate analysis and combustion showed that lower Volatile Matter (VM) and higher fixed carbon contents contributed to improved thermal stability and controlled combustion behavior. These findings confirm that torrefaction at 275°C combined with a 15% HDPE binder produces high-quality biopellets with superior mechanical strength, hydrophobicity, and combustion performance, making them a promising candidate for sustainable and efficient bioenergy systems.

### Keywords:

Elephant grass, HDPE plastic, biopellet, torrefaction

## 1 Introduction

The increasing global demand for energy, driven by industrialization and population growth, remains heavily dependent on fossil fuels [1]. This reliance not only accelerates the depletion of non-renewable resources but also significantly contributes to greenhouse gas emissions and environmental degradation. Consequently, the development of alternative and renewable energy sources has become an urgent global priority to ensure sustainable energy security and mitigate climate change [2].

Technological advancements have shifted the focus from first-generation feedstocks such as corn [3] and sugarcane [4] to second-generation biomass sources, including non-edible energy crops and

king grass [5]. These second-generation sources offer ecological advantages as they require less water and fertilizer and thrive on marginal lands, thereby preserving fertile soils for food production and reducing the environmental footprint of biomass cultivation [6]. Among various types of grasses, *Pennisetum purpureum*, commonly known as Napier grass or Elephant Grass (EG), has gained considerable attention due to its vigorous growth and minimal resource requirements [7]. EG can grow in diverse climates, is drought-resistant, and produces high yields on marginal soils, making it ideal for sustainable biomass energy production. However, its direct use as a fuel faces several challenges, such as high moisture content, low bulk density, and poor storage stability, which limit its efficiency in combustion and energy conversion processes. Its rapid growth and suitability for repeated harvesting make it an economically viable option for farmers in both developed and developing countries [8]. In addition to providing a renewable energy source, EG also aids in land management and erosion control, enhancing its ecological value [9].

Accordingly, appropriate pretreatment and densification (e.g., torrefaction and pelletization) are required to improve its fuel quality and handling characteristics. Torrefaction is one of the mild thermochemical pretreatment processes conducted at relatively low temperatures of 200–300°C [8]. During heating, biomass decomposes and releases condensable volatiles (bio-oil), while the remaining solid residue is a carbon-rich biochar. Despite these advantages, torrefied biomass often exhibits low mechanical strength and high brittleness, which may hinder its utilization in biopellet production. To overcome these limitations, polymer-based binders such as high-density polyethylene (HDPE) waste can be added as additives to enhance pellet durability and combustion characteristics [9].

The integration of biomass and plastic waste in biopellet production offers dual benefits: providing a renewable energy source while simultaneously addressing plastic waste management issues. HDPE, a thermoplastic polymer with a high calorific value, can serve as an effective binder and energy enhancer when mixed with torrefied biomass. However, comprehensive studies that systematically evaluate the physicochemical, mechanical, water-resistance, and combustion characteristics of torrefied elephant grass biopellets combined with waste HDPE remain limited. The novelty of this study lies in developing torrefied elephant grass-based composite biopellets using waste HDPE as a binder and providing an integrated assessment across two torrefaction temperatures (225°C and 275°C) and multiple HDPE contents (0–20 wt%) to identify an optimal multi-criteria condition.

Therefore, this study aims to investigate the production and characterization of biopellets made from torrefied elephant grass blended with HDPE plastic waste. The research focuses on evaluating the proximate composition, calorific value, apparent density, drop resistance, hydrophobicity, and combustion performance. In addition, particle size distribution analysis is conducted to further understand the physical properties influencing fuel performance. The findings of this study are expected to provide valuable insights into the potential of combining agricultural biomass and plastic waste for the development of sustainable solid fuels.

## 2 Material and methods

### 2.1 Materials preparation

Two materials that are abundant in Indonesian communities but are not yet utilized as fuel sources are elephant grass (*Pennisetum purpureum*) and HDPE plastic. The elephant grass was collected from local plantations in North Aceh Regency, Aceh Province, Indonesia. The grass was washed with tap water to remove dirt and reduce ash content. The raw material was then sun-dried for 4–5 days. After drying, the grass was cut into pieces approximately 5 cm in length. The cut length was maintained at approximately 5 cm ( $\pm 0.5$  cm) to ensure a relatively uniform feed size and more consistent heat transfer during torrefaction.

The HDPE plastic was collected and cleaned, then cut into pieces of about 5 cm. The cut HDPE was subsequently heated to a temperature of 120°C, molded, and cooled into sheet form to facilitate cutting into small cube-sized pieces. These cubes were then crushed and sieved to pass through a 20-mesh screen.

## 2.2 Torrefaction experiment

The torrefaction process was carried out using a retort kiln reactor [10]. In each experiment, the dried elephant grass was placed into the retort kiln and heated to temperatures of 225°C and 275°C with a residence time of 30 minutes. The residence time of 30 minutes refers to the holding time at the target temperature, while the total process duration ( $\approx 200$  minutes) includes the heating and cooling stages in addition to the holding period. The heating rate was maintained at approximately 7–8 °C/min from ambient temperature to the target temperature. The retort kiln reactor was secured with clamping bolts to ensure no leakage occurred during the reaction. The fuel used in the torrefaction process is used oil. After completion, the products obtained consisted of biochar and bio-oil. The resulting biochar was then ground and sieved to pass through a 20-mesh screen.

## 2.3 Pelletizing process

The ground biochar was mixed with an HDPE binder that had also passed through a 20-mesh sieve, with variations of 0, 5, 10, 15, and 20%. HDPE content was expressed as weight percentage (wt%) of the total mixture (biomass + HDPE) before pelletization. The mixture was stirred until homogeneous and then fed into a laboratory-scale pelletizing machine [11]. The machine was equipped with an 8 mm diameter mold, powered by a 1.5 kW Wey-90L1-2 motor, with a capacity of 5 kg and an operating time of 30 minutes. Pelletization was conducted without external heating. Therefore, an HDPE softening/melting was driven by frictional heating inside the die during extrusion. The produced bio pellets were sun-dried for 5–7 days to reduce moisture content. Once dried, the bio pellets were packed in plastic bags and stored for further analysis.

## 2.4 Product characterization

The sample preparation for the experiments is summarized in Table 1. To characterize the bio pellets made from elephant grass with an HDPE binder, a series of analyses was conducted, including proximate analysis, apparent density, mechanical durability, calorific value, and combustion performance. All measurements were performed in triplicate ( $n = 3$ ) and reported as mean  $\pm$  SD. Proximate analysis was performed to determine moisture content, Volatile Matter (VM), fixed carbon, and ash content according to ASTM D7582-15 [12]. The apparent density was calculated from the external volume of the pellet. The pellet diameter and length were measured using a micrometer, and the total pellet volume was calculated assuming a cylindrical shape. Mechanical durability was evaluated using a modified mechanical durability method. The bio pellets were dropped from a height of 1.0 m onto a rigid steel surface for 10 consecutive drops per replicate [13]. The mechanical durability (%) was calculated as the ratio of the mass retained after the mechanical durability to the initial mass multiplied by 100. All measurements were performed in triplicate ( $n = 3$ ).

Table 1. Sample ID

Sample	Description
TEG225-P0	Torrefied elephant grass pellet at 225°C
TEG225-P5	Torrefied elephant grass pellet at 225°C with 5% HDPE plastic
TEG225-P10	Torrefied elephant grass pellet at 225°C with 10% HDPE plastic
TEG225-P15	Torrefied elephant grass pellet at 225°C with 15% HDPE plastic
TEG225-P20	Torrefied elephant grass pellet at 225°C with 20% HDPE plastic
TEG275-P0	Torrefied elephant grass pellet at 275°C
TEG275-P5	Torrefied elephant grass pellet at 275°C with 5% HDPE plastic
TEG275-P10	Torrefied elephant grass pellet at 275°C with 10% HDPE plastic
TEG275-P15	Torrefied elephant grass pellet at 275°C with 15% HDPE plastic
TEG275-P20	Torrefied elephant grass pellet at 275°C with 20% HDPE plastic

The calorific value of the samples was determined using a Parr 6200 Bomb Calorimeter. The samples were placed in an alumina crucible and heated from ambient temperature up to 1000°C. The direct combustion test was conducted following the method described in [8], [14]. Approximately 50 g of wet-torrefied elephant grass pellets were placed in the combustion chamber and ignited with 20 g of ethanol. During the test, the pellet mass was monitored using a digital balance, the burning time was recorded with a stopwatch, and the temperature was measured using a Type K thermocouple.

## 3 Results and discussions

### 3.1 Torrefaction experiment of elephant grass

Fig. 1 shows the temperature profile during the torrefaction process of elephant grass conducted at 225°C and 275°C using a retort furnace. Both temperature curves exhibit a sharp increase during the initial heating phase (0–30 minutes), corresponding to rapid heat transfer and moisture evaporation from the biomass. After approximately 30 minutes, the system reached a relatively stable temperature, indicating that the retort furnace was capable of maintaining a uniform heat distribution under quasi-steady-state conditions throughout the process duration of about 200 minutes.

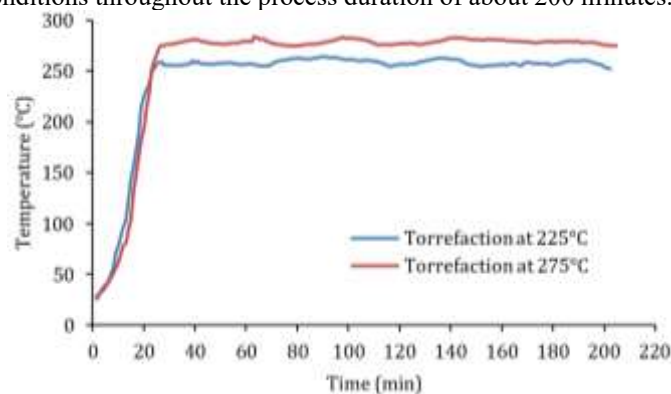


Fig. 1. Temperature profile recorded during the torrefaction of elephant grass

During the initial stage, the sharp temperature rise indicates the drying and devolatilization of low-molecular-weight compounds such as free and bound water, acetic acid, and light volatiles. Once the target temperature is reached, the process enters the thermochemical decomposition stage, dominated by hemicellulose degradation at 200–260°C, followed by partial cellulose decomposition at temperatures above 260°C. According to Tumuluru, et al. (2011), hemicellulose is the most thermally unstable component of lignocellulosic biomass, which decomposes early during mild torrefaction, resulting in a significant reduction in mass and an increase in the energy density of the solid product [15].

At 225°C, the solid yield decreased from 5.112 kg to 2.145 kg, corresponding to a mass yield of approximately 42.0%. Meanwhile, at 275°C, the yield decreased from 5.145 kg to 2.112 kg, resulting in a mass yield of around 41.0%. This reduction in yield was due to the release of volatile organic compounds (CO<sub>4</sub>, CO, CH<sub>4</sub>, and light tars), which became more pronounced at higher temperatures. As the torrefaction temperature increased, the intensity of devolatilization also increased, leading to a more carbon-rich and hydrophobic material with higher fixed carbon content but lower solid yield [16], [17].

However, despite the lower solid yield at 275°C, the torrefied material generally exhibited better energy quality, including higher calorific value, lower moisture content, and greater resistance to moisture reabsorption. As noted by Bridgeman, et al. (2018) and Chen et al. (2010), the severity of torrefaction is inversely proportional to solid yield but directly enhances fuel quality and combustion efficiency [18], [19].

This phenomenon reflects the inherent trade-off in the torrefaction process: higher temperatures and longer residence times produce superior fuel characteristics at the expense of lower solid yield. The stable temperature profiles observed in both experiments further confirm that the retort furnace used in this study was capable

of maintaining consistent thermal conditions, ensuring uniform carbonization of the elephant grass.

### 3.2 Bio pellet morphology and size distribution

The particle size distribution is an important parameter for evaluating the physical quality and performance of biomass pellets

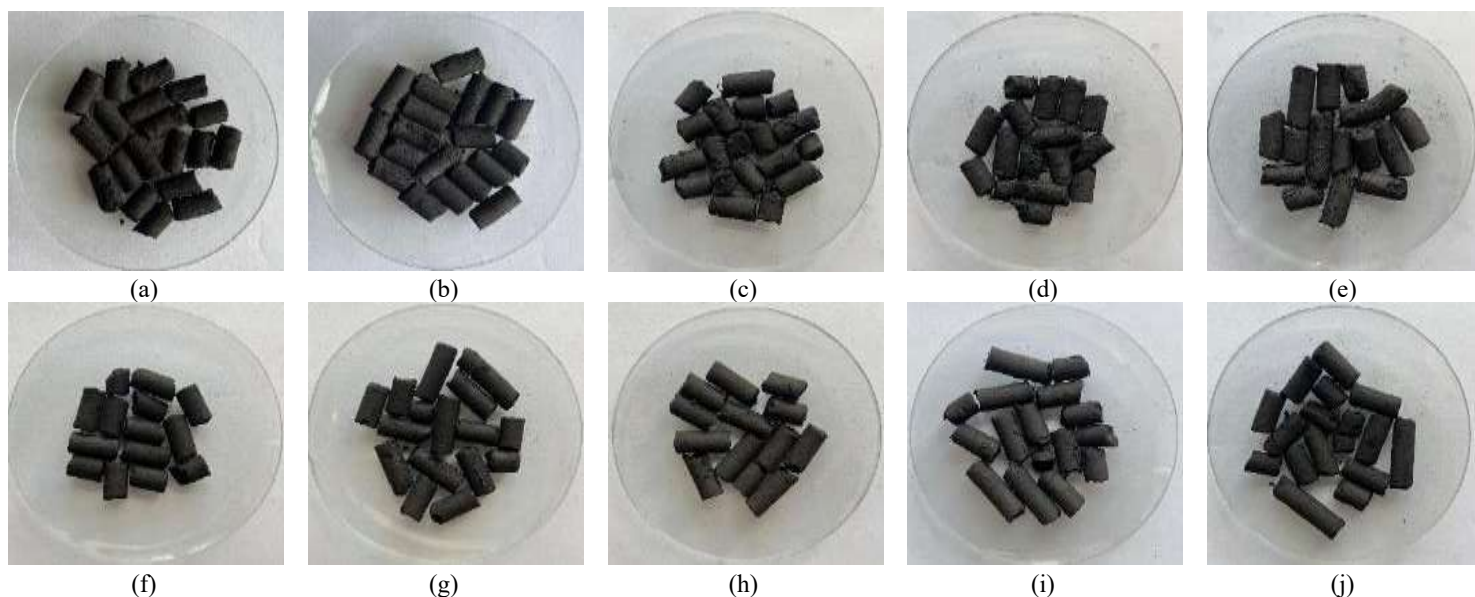


Fig. 2. The image of biopellet product of (a) TEG225-P0; (b) TEG225-P5; (c) TEG225-P10; (d) TEG225-P15; (e) TEG225-P20; (f) TEG275-P0; (g) TEG275-P5; (h) TEG275-P10; (i) TEG275-P15; (j) TEG275-P20

Fig. 3 shows the size distribution of elephant grass biopellets, indicating that most pellets fall within the 15–20 mm range, accounting for 43% of the total size distribution. Pellets with lengths between 20–25 mm represent 24%, those between 10–15 mm make up 22%, and shorter pellets (5–10 mm) contribute 10%. The smallest proportion (1%) consists of pellets in the 25–30 mm range.

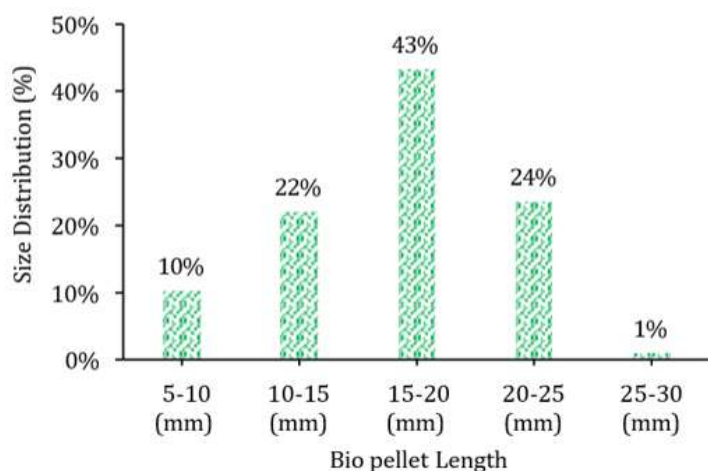


Fig. 3. Size distribution of bio-pellet product

This distribution pattern demonstrates that the pelletizing process produced a relatively uniform product, with the majority of pellets within the optimal range recommended by ISO 17225-2, which specifies that wood and biomass pellets should have lengths between 3.15 mm and 40 mm, and typically 5–20 mm for efficient combustion and handling [20]. The predominance of pellets in the 15–20 mm category indicates effective control during the extrusion and cutting stages of pelletization, resulting in consistent pellet geometry and minimal variation in product length.

The presence of smaller pellets (5–10 mm) and a small fraction of longer ones (>25 mm) can be attributed to inconsistent feed rates, variations in compression pressure, or fragmentation during cooling and handling. According to Stelte, *et al.* (2011), pellet size variation is strongly influenced by the moisture content of the raw material, die temperature, and frictional forces during extrusion, all of which determine the degree of plasticization and bonding between biomass fibers [21].

as solid biofuels. This parameter affects combustion behavior, energy density, handling, and transport properties. Fig. 2 presents the produced biopellet products.

A balanced size distribution, as observed in this study, is advantageous for uniform combustion, transportation, and storage efficiency. Pellets within the 15–20 mm range promote stable fuel feeding in combustion systems, minimize dust formation, and enhance bulk density consistency, thereby improving mechanical strength and reducing material losses during handling [22]. Conversely, shorter pellets (<15 mm) tend to ignite and burn faster due to their higher surface area-to-volume ratio, while excessively long pellets (>25 mm) may cause bridging or feeding issues in automatic combustion systems [23].

The predominance of pellets sized 15–20 mm also reflects the effectiveness of the torrefaction pretreatment applied to elephant grass. Torrefaction enhances the brittleness and grindability of lignocellulosic biomass, resulting in finer particles that form more uniform pellets during compaction. Furthermore, thermal degradation of hemicellulose during torrefaction generates low-molecular-weight organic compounds (e.g., furfural, acetic acid, and water-soluble tars) that can act as natural binding agents during pellet formation [24]. This explains the improved cohesion and mechanical integrity of the pellets, leading to consistent size distribution and reduced formation of fine particles.

### 3.3 Product characterization

#### 3.3.1 Physical and mechanical properties

Proximate analysis (moisture content, ash content, VM, and fixed carbon), apparent density, drop resistance, and calorific value of the elephant grass biopellet products are summarized in Table 2. These parameters collectively determine the fuel quality of the biopellets as influenced by variations in torrefaction temperature and the addition of HDPE plastic as a binder.

The moisture content of the bio pellets decreased with increasing HDPE content and torrefaction temperature. At 225°C, the moisture content dropped from 6.99% (TEG225-P0) to 4.67% (TEG225-P20), while at 275°C, it further decreased to 2.67% (TEG275-P20). This trend indicates that higher torrefaction temperatures promote dehydration and devolatilization, resulting in a more hydrophobic material. The reduction in moisture content is crucial for improving combustion efficiency and pellet storage stability [24]. The addition of HDPE also contributed to this reduction because plastic polymers do not absorb water and can encapsulate biomass particles, thereby limiting water reabsorption [25].

Ash content slightly increased with increasing HDPE mixing ratio and temperature, ranging from 1.43–2.68% (225°C) and 1.45–3.15% (275°C). The increase at higher torrefaction temperatures

(275°C) can be attributed to the concentration effect of inorganic components after the evaporation of organic matter.

Table 2. Physical and Mechanical Properties of biopellet elephant grass (mean  $\pm$  SD, n = 3)

Sample ID	Parameters					
	Moisture content (%)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)	Apparent density (g/cm <sup>3</sup> )	Mechanical durability (%)
TEG225-P0	6.99 $\pm$ 0.85	1.43 $\pm$ 0.41	72.02 $\pm$ 3.48	19.57 $\pm$ 3.29	0.814 $\pm$ 0.67	71.587 $\pm$ 3.06
TEG225-P5	5.55 $\pm$ 0.42	1.64 $\pm$ 0.30	69.59 $\pm$ 4.29	23.23 $\pm$ 4.04	0.723 $\pm$ 0.52	76.442 $\pm$ 3.51
TEG225-P10	5.26 $\pm$ 0.31	1.72 $\pm$ 0.23	67.11 $\pm$ 5.72	24.55 $\pm$ 3.22	0.699 $\pm$ 0.21	87.329 $\pm$ 1.53
TEG225-P15	5.08 $\pm$ 0.26	2.47 $\pm$ 0.37	64.49 $\pm$ 7.02	27.96 $\pm$ 6.84	0.708 $\pm$ 0.32	87.869 $\pm$ 2.00
TEG225-P20	4.67 $\pm$ 0.48	2.68 $\pm$ 0.38	62.8 $\pm$ 6.85	29.86 $\pm$ 6.48	0.616 $\pm$ 0.45	93.497 $\pm$ 0.58
TEG275-P0	6.62 $\pm$ 0.79	1.45 $\pm$ 0.30	47.27 $\pm$ 1.66	38.62 $\pm$ 4.91	0.799 $\pm$ 0.89	74.847 $\pm$ 3.00
TEG275-P5	5.46 $\pm$ 1.05	1.71 $\pm$ 0.20	43.84 $\pm$ 1.37	43.69 $\pm$ 4.46	0.814 $\pm$ 0.23	77.141 $\pm$ 4.58
TEG275-P10	4.25 $\pm$ 0.62	2.21 $\pm$ 0.22	42.41 $\pm$ 0.71	47.01 $\pm$ 3.47	0.847 $\pm$ 0.48	85.664 $\pm$ 1.00
TEG275-P15	3.67 $\pm$ 0.64	2.59 $\pm$ 0.17	38.41 $\pm$ 2.16	51.99 $\pm$ 1.61	0.875 $\pm$ 0.21	87.232 $\pm$ 3.06
TEG275-P20	2.67 $\pm$ 0.60	3.15 $\pm$ 0.15	34.5 $\pm$ 2.07	56.93 $\pm$ 0.70	0.864 $\pm$ 0.14	94.995 $\pm$ 3.61

Moreover, the presence of HDPE may not directly contribute to ash formation, but its combustion residue and possible incomplete oxidation at elevated temperatures could cause a slight increase [26]. Although the observed ash content remains relatively low, maintaining it below 5% is still desirable to minimize slagging and fouling during combustion [27].

VM content decreased substantially with increasing temperature and HDPE concentration, from 72.02%  $\rightarrow$  62.80% (225°C) and 47.27%  $\rightarrow$  34.50% (275°C). Conversely, fixed carbon (FC) content increased from 19.57%  $\rightarrow$  29.86% (225°C) and 38.62%  $\rightarrow$  56.93% (275°C). This inverse relationship reflects the carbonization level of the biomass during torrefaction. Higher temperatures promote the thermal decomposition of hemicellulose and cellulose, releasing volatile compounds (e.g., CO<sub>2</sub>, CO, CH<sub>4</sub>, acetic acid, and tar) and leaving behind a carbon-rich solid matrix [18]. The HDPE component, which is highly carbonaceous, further enhances the fixed carbon density and energy content due to its high calorific value and low oxygen content [28]. This behavior is consistent with the findings of Chen et al. (2015), who reported that torrefied biomass exhibits reduced oxygen content and increased fixed carbon, thereby improving fuel properties and combustion stability [24].

The apparent density of the biopellets ranged from 0.616 to 0.875 g/cm<sup>3</sup>, with a general increase observed at higher HDPE additions, particularly at 275°C. This densification improvement is likely due to the melting of HDPE and its ability to fill voids between biomass particles, acting as a binder that enhances compactness. At higher temperatures (275°C), partial softening of lignin (a natural binder in

biomass) and the melting of HDPE likely improved interparticle adhesion and reduced porosity, resulting in denser pellets. Similar results were reported by Stelte, et al. (2011), who emphasized the role of thermal softening in improving pellet strength and density [21].

Mechanical durability, represented by the mechanical durability, showed a strong positive correlation with both HDPE addition and torrefaction temperature. At 225°C, the durability increased from 71.6% to 93.5%, while at 275°C, it rose from 74.8% to 95.0%. This indicates that HDPE effectively acts as a binding agent, enhancing the mechanical integrity of the pellets [29]. In addition, torrefaction reduces moisture and VM, thereby improving structural rigidity and hydrophobicity, both of which contribute to greater mechanical strength [30].

### 3.3.2 Hydrophobicity

Analysis of hydrophobic properties was conducted using the Water Droplet Penetration Time (WDPT) test to determine the water absorption behavior of the elephant grass biopellets. The hydrophobic results are presented in Fig. 4.

The increase in hydrophobicity with HDPE addition can be attributed to the nonpolar nature of polyethylene, which consists solely of C–C and C–H bonds. These bonds are highly resistant to hydrogen bonding with water molecules, thereby reducing wettability. During the pelletization process, HDPE melts and forms a thin, continuous coating over the biomass particles, effectively sealing surface pores and cracks that could otherwise allow water ingress [17].

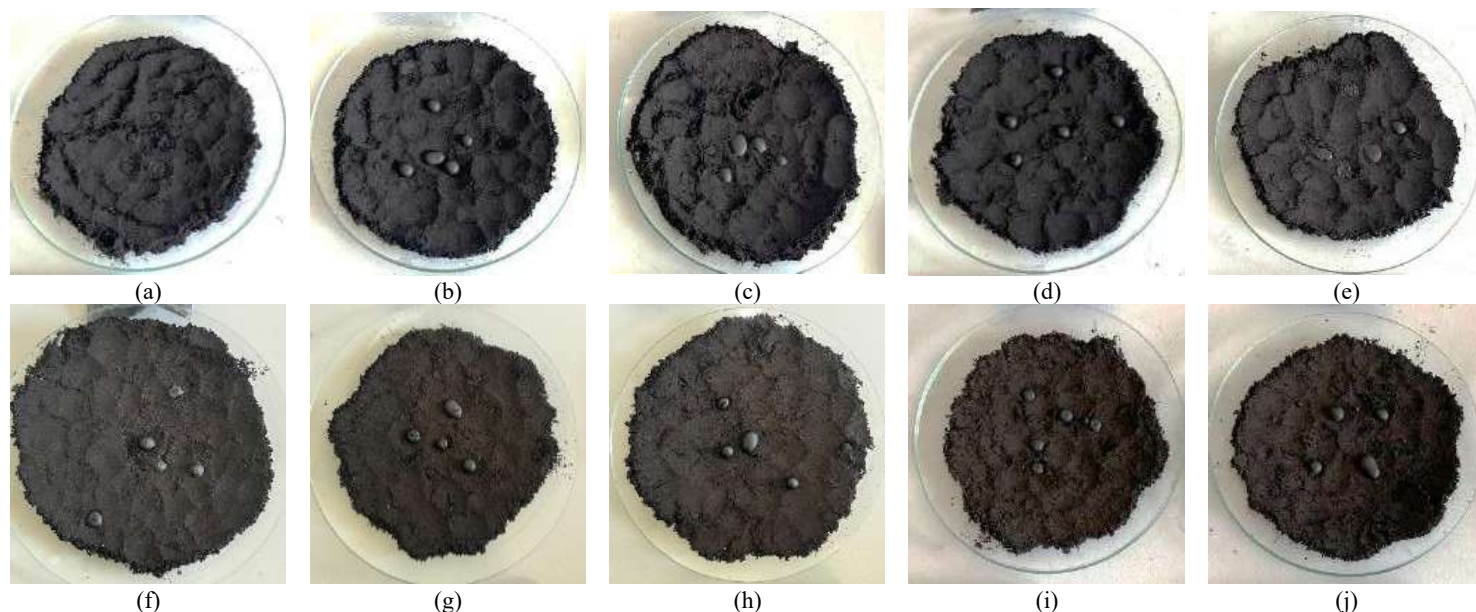


Fig. 4. Type of hydrophobic of torrefied biomass: (a) TEG225-P0; (b) TEG225-P5; (c) TEG225-P10; (d) TEG225-P15; (e) TEG225-P20; (f) TEG275-P0; (g) TEG275-P5; (h) TEG275-P10; (i) TEG275-P15; (j) TEG275-P20

This surface coating mechanism enhances the hydrophobic ability of the pellets, as evidenced by the significant increase in water penetration time from 92.2 seconds (TEG225-P0) to 151.4 seconds (TEG225-P20). A similar trend was reported by Bhushan, et al. (2025), who found that the addition of thermoplastic polymers such as polyethylene or polypropylene to biomass pellets improves moisture resistance and dimensional stability [31].

The torrefaction process itself contributes to the intrinsic hydrophobic properties of biomass. At elevated temperatures (225°C–275°C), oxygen-containing functional groups such as hydroxyl (–OH), carbonyl (C=O), and carboxyl (–COOH) are thermally decomposed, leading to a reduction in the O/C and H/C ratios. This transformation results in a more carbonaceous and less polar surface, thereby reducing water affinity [24], [32].

However, the data reveal an interesting trend: samples torrefied at 275°C do not necessarily exhibit higher hydrophobicity than those torrefied at 225°C. For instance, TEG275-P20 recorded a water penetration time of only 37.4 seconds, significantly lower than TEG225-P20 (151.4 seconds). This anomaly suggests that excessive torrefaction severity can cause microcrack formation and surface degradation, increase surface porosity, and allow faster water penetration [21].

Furthermore, thermal decomposition of HDPE at higher torrefaction temperatures may partially impair its protective coating function. HDPE begins to soften and degrade above 270°C, releasing hydrocarbons and reducing its ability to form a continuous

hydrophobic layer [31]. Therefore, achieving an optimal torrefaction–HDPE balance is crucial to maintaining structural integrity and hydrophobic resistance.

Enhanced hydrophobicity directly contributes to better storage stability and mechanical durability of pellets under humid conditions. Water absorption typically causes swelling, cracking, and disintegration of biomass pellets, reducing their mechanical strength and calorific value. In contrast, the highly hydrophobic pellets produced in this study are expected to maintain their structural integrity and energy quality during long-term storage and transportation.

However, the slightly lower hydrophobicity observed in TEG275-P20 indicates a possible degradation threshold for HDPE–biomass composites under high thermal stress. Process optimization at moderate torrefaction temperatures (225°C–250°C) with an HDPE addition of 10–15% appears ideal for preserving hydrophobic characteristics and overall pellet performance.

### 3.3.3 Rate of combustion

The temperature change over time during the combustion process of elephant grass–HDPE mixed bio pellets exhibited a characteristic thermal pattern influenced by the degree of torrefaction and the proportion of added plastic, as shown in Fig. 5. In the initial stage of combustion, the temperature rose rapidly due to the devolatilization process, which involves the evaporation of easily volatile compounds from the biomass matrix. Samples torrefied at the lower temperature (225°C) exhibited a sharper temperature rise compared to those torrefied at 275°C, since the higher volatile content facilitated the release of combustible gases such as CO, CH<sub>4</sub>, and other light hydrocarbons. This phenomenon is consistent with the proximate analysis results, which showed that the VM content in TEG225-P0 reached 72.02%, whereas in TEG275-P20 it was only around 34.50%.

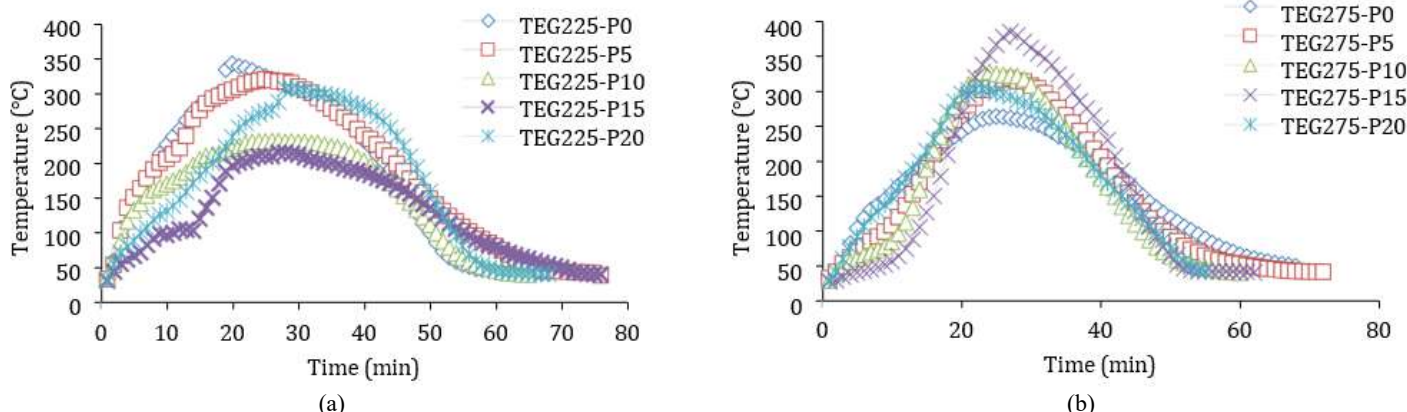


Fig. 5. Combustion temperature as a function of time of biopellet derived from elephant grass torrefied at (a) 225°C; (b) 275°C

In the subsequent combustion phase, namely the char oxidation stage, the temperature rise occurred more slowly but steadily. Samples torrefied at 275°C exhibited higher peak temperatures and longer peak durations. This behavior is attributed to the increased fixed carbon content resulting from more complete thermal decomposition of lignocellulosic components during torrefaction, which produces a denser, more energy-rich material. The higher fixed carbon content prolongs the char combustion process and sustains elevated temperatures for a longer period, as also described by [17], [33].

The addition of HDPE had a significant influence on the temperature profile. In samples containing 5–15% HDPE, the initial temperature rise occurred more rapidly compared to samples without HDPE. This is because HDPE possesses a high calorific value and begins to melt and combust at around 350–400°C, releasing additional heat energy that accelerates the temperature increase. However, at excessively high HDPE concentrations (around 20%), the peak temperature slightly decreased. This phenomenon can be attributed to the formation of a molten plastic layer on the pellet surface, which may hinder oxygen diffusion into the biomass matrix and result in incomplete oxidation [34]. Overall, the combination of torrefaction at 275°C and an HDPE addition of 10–15% provided

the most stable combustion temperature profile, with the highest peak temperature and optimal combustion duration.

Furthermore, the low moisture content in pellets torrefied at higher temperatures also contributed to the stability of combustion temperature. Pellets with lower moisture levels (around 2–3%) required less evaporation energy, allowing the generated heat to be more effectively utilized for oxidation reactions. This led to a faster and more stable temperature rise throughout the combustion process [25]. In general, the temperature variation trends indicate that increasing the torrefaction temperature and appropriately adding HDPE play crucial roles in enhancing combustion efficiency and the thermal characteristics of the bio pellets.

The mass change over time during the combustion process, as illustrated in Fig. 6, shows three main stages that describe the thermogravimetric behavior of the bio pellets: drying, devolatilization, and char oxidation. In the initial stage (0–100°C), the mass loss was relatively small, primarily due to the evaporation of free moisture from the pellet structure. Samples torrefied at 275°C experienced smaller initial mass losses due to their lower moisture content, whereas those torrefied at 225°C showed greater initial mass reduction because of higher moisture levels.

The second stage (100–400°C) was characterized by the most rapid mass loss. In this temperature range, the devolatilization

process occurred, during which volatile compounds such as hemicellulose and part of the cellulose decomposed to release combustible gases. The TEG225 samples exhibited a higher rate of mass reduction compared to TEG275, owing to their greater volatile content. This process caused the mass–time curve for TEG225 to decline sharply during the early phase of combustion, whereas TEG275 showed a slight but more sustained decrease in mass. This

pattern indicates that torrefaction reduces the content of volatile components and enhances the thermal stability of the material [15]. The third stage (400–600°C) corresponded to the char oxidation phase, where the residual mass continued to decrease gradually. At this stage, the mass loss rate was primarily influenced by the fixed carbon content and the physical structure of the pellets [35].

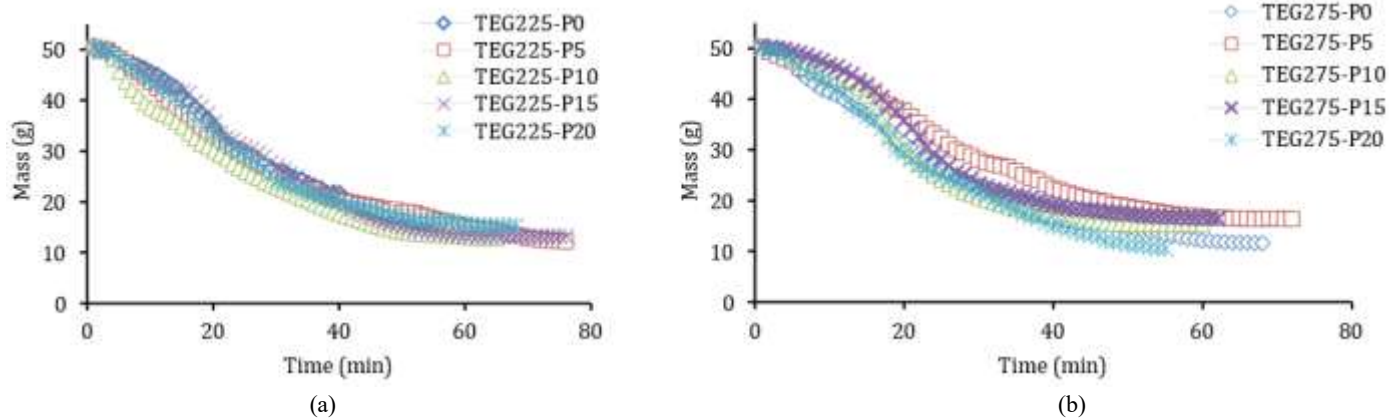


Fig. 6. Mass loss versus time during combustion process of biopellet derived from elephant grass torrefied at (a) 225°C; (b) 275°C

Samples subjected to higher torrefaction temperatures had greater fixed carbon content and denser structures, leading to slower but more stable combustion. Conversely, samples torrefied at lower temperatures experienced faster oxidation but left behind a larger amount of ash residue. The addition of HDPE also affected the mass loss profile: at concentrations of 5–10%, HDPE enhanced the total combustion energy, resulting in a faster mass reduction during the initial combustion phase. However, at higher concentrations (20%), the rate of mass loss decreased due to the formation of a molten plastic layer that limited oxygen diffusion and slowed the oxidation process.

The correlation between mass loss and proximate analysis results demonstrates a strong relationship between chemical composition and combustion behavior. Samples with high volatile content (TEG225-P0) exhibited a sharp mass decrease at the beginning of combustion, whereas samples with high fixed carbon content (TEG275-P15) showed a more gradual and stable rate of mass reduction. Moreover, the increased pellet density resulting from torrefaction and HDPE addition contributed to a smoother mass loss profile without abrupt drops, indicating more uniform combustion. These results are consistent with the findings of Stelte, et al. (2011), who reported that higher pellet density and mechanical strength improve thermal stability during combustion [21]

Overall, the mass change profile over time suggests that the combination of higher torrefaction temperature (275°C) and moderate HDPE addition (10–15%) produced pellets with optimal thermal stability and combustion performance. This finding indicates that controlling both the composition and torrefaction process conditions is a key factor in determining the thermal conversion efficiency of bio pellets during combustion.

#### 4 Conclusions

The torrefaction of elephant grass at 225°C and 275°C significantly influenced the physicochemical and combustion characteristics of the resulting bio pellets. The temperature profile indicated that increasing the torrefaction temperature enhanced the decomposition of hemicellulose and cellulose, resulting in a substantial reduction in solid yield of 41.96% at 225°C and 41.05% at 275°C. Proximate analysis revealed a consistent decrease in moisture and VM content, accompanied by an increase in fixed carbon and ash content with higher torrefaction temperatures and HDPE binder addition. These transformations improved the energy density and thermal stability of the pellets. The mechanical properties, represented by apparent density and mechanical durability values, increased with the addition of HDPE, confirming

its role as a structural reinforcement and binder. Furthermore, the hydrophobic properties of the pellets improved, as indicated by longer water penetration times, although excessive HDPE at 275°C caused minor degradation and a slight reduction in surface resistance. Combustion analysis showed that pellets torrefied at 275°C exhibited a faster temperature rise and a more gradual mass loss, indicating improved combustion efficiency and thermal endurance. Overall, the findings demonstrate that the combination of a torrefaction temperature of 275°C and 15% HDPE binder yields bio pellets with optimal performance in terms of mechanical integrity, hydrophobic behavior, and combustion stability, supporting their potential as durable and efficient solid biofuels for sustainable energy production.

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