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Evaluation of Fuel Performance of Torrefied Rice Husk-LDPE Nuggets: Influence of Temperature and Residence Time on Combustion Properties

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Abstract: *The study aimed at production of rice husk and low-density polyethylene (LDPE) waste nugget using torrefaction technique, evaluation of proximate, fuel performance and surface morphological analysis of the nugget samples. Results from torrefaction technique revealed that different samples of rice husk-nuggets were produced under 250°C at 30 mins and 60 mins respectively and 300°C at 30 mins and 60 mins respectively. This research emphasizes the morphological and visual changes occurring in rice husk-LDPE waste nuggets through torrefaction at different temperatures and time intervals. Gradual darkening, elevated porosity, increased surface roughness, and structural fragmentation that was observed highlight the thermal degradation processes that enhance surface area, reactivity, and carbon content, thereby optimizing fuel quality and performance tailored to specific applications. Proximate analyses results on moisture content (MC), volatile matter (VM), ash content (AC), fixed carbon content (FCC), calorific value (CV), and flammability characteristics obtained with the aid of thermogravimetric technique revealed that temperature increase together with residence time significantly improves the fuel performance (as evidenced by reduced MC (down to 0.39%), VM (as low as 0.02%), and AC (minimum 3.81%), while markedly increasing FCC (up to 98.95%) and CV (maximum 8,539.45 Kcal/kg)) of the nugget samples. Thus, these trends confirm that longer residence time and higher temperature enhance carbonization, thermal stability and energy density. In addition, flammability results confirmed that nugget samples demonstrated rapid ignition, reduced glow time and controlled self-extinguishing behaviour particularly at 300°C for 60 mins, thus suggesting the attributes that are critical for blacksmith forge and other high-temperature artisanal applications. It is clear from these results that synergy between biomass from rice husk and LDPE waste under optimized torrefaction conditions positioned the nuggets as composite with sustainable characteristics and high biofuels potentials.*

Keywords*: Torrefaction, Nuggets, LDPE Waste, Fuel, Calorific Value.*

I. Introduction

The increasing global emphasis on sustainable energy development and decentralized energy systems has driven research into the valorisation of agricultural biomass and the recovery of synthetic waste materials. In sub-Saharan Africa, where energy poverty persists and rural industries such as blacksmithing depend heavily on traditional biomass fuels, the need for clean, locally sourced, and energy-dense fuel alternatives is critical (Hussein & Leal, 2012). This study responds to that need by exploring the integration of agricultural waste, specifically rice husk with low-density polyethylene (LDPE) waste, into a torrefied nugget biofuel suitable for

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forging applications. Rice husk is a prominent agro-residue produced during the de-husking of paddy rice, typically accounting for approximately 20% of the harvested grain weight (Friedl et al., 2005). In rice-producing regions such as Nigeria, the husk is often discarded via open-air combustion, contributing to significant environmental degradation through the release of carbon monoxide, particulate matter, sulphur oxides, and volatile organic compounds (Chang, 2013; Sun & Cheng, 2002). Despite its high fixed carbon potential and abundance, the direct use of rice husk as a fuel is limited by its low bulk density, high ash content, and inconsistent combustion profile.

LDPE has emerged as a pervasive environmental pollutant. Widely used in packaging, agriculture, and domestic applications, it is characterized by its resistance to microbial degradation, which renders it a long-lasting contaminant in terrestrial and aquatic ecosystems (Mirmohamadsadeghi & Karimi, 2020). However, this thermoplastic polymer possesses properties that are advantageous for energy applications, particularly its high calorific value (~43 MJ/kg) and its ability to act as a binder at elevated temperatures. When thermally activated, LDPE transitions into a viscous phase that facilitates the cohesion of particulate materials, thereby enabling the formation of mechanically stable fuel composites.

Torrefaction, a mild thermochemical pre-treatment conducted between 200 and 300 °C in a limited oxygen environment, offers a viable strategy for upgrading biomass for energy use. The process significantly enhances the energy density, hydrophobicity, and structural stability of lignocellulosic materials by degrading hemicellulose and reducing moisture and volatile matter content, while increasing fixed carbon (Bourgois & Guyonnet, 1988; Pach et al., 2002). For rice husk, torrefaction is particularly beneficial as it mitigates the slagging and fouling issues typically caused by its high silica content, while also improving combustibility and storage stability.

The integration of LDPE into torrefied rice husk during thermal processing enables a co-valorisation pathway that addresses waste management and energy generation within a unified framework. As LDPE melts, it encapsulates the biomass particles, thereby increasing nugget density, mechanical strength, and thermal integrity. Studies have shown that such composite fuel nuggets display enhanced combustion performance, reduced smoke and tar formation, and improved resistance to moisture re-absorption during storage (Zhang et al., 2022). These properties are of particular relevance in small-scale blacksmith forges, where consistent high-temperature output, low-residue combustion, and mechanical resilience under thermal cycling are essential operational requirements. Moreover, the development of these bio-composite fuels contributes to circular economy objectives by diverting LDPE waste from landfills and converting it into a functional energy product. The dual valorisation of rice husk and LDPE exemplifies an integrated waste-to-energy approach, offering both environmental and economic benefits. In off-grid contexts where reliance on firewood and charcoal remains prevalent, such alternatives can mitigate deforestation and reduce the carbon footprint of rural industries.

LDPE-biomass based energy is emerging as a sustainable solution to reduce reliance on fossil fuels, particularly in agricultural economies where lignocellulosic residues, such as rice husks, are abundant but underutilized. Co-torrefaction, the process of combining these biomass residues with waste plastics like low-density polyethylene (LDPE) and polypropylene (PP), has gained significant attention for its ability to enhance the fuel properties of the resulting biofuels (Saha et al., 2025). This method not only increases the calorific value, mechanical stability, and moisture resistance of the biofuel but also improves the higher heating values (HHV) and structural integrity, making the biofuels more suitable for applications such as briquetting. By integrating rice husks with LDPE, co-torrefaction offers a promising solution for regions facing both agricultural and plastic waste challenges, thus providing a renewable, sustainable fuel alternative that addresses both energy needs and environmental concerns.

The inclusion of plastic waste not only enhances fuel characteristics but also supports circular economy goals by reducing landfill waste. This study investigates the production and physio-thermal characterization of torrefied nuggets derived from rice husk and LDPE waste. The experimental focus lies in optimizing torrefaction parameters to enhance fuel quality and assessing key fuel properties including proximate composition, calorific value, combustion behaviour, flammability, and mechanical strength. Through systematic characterization, the research aims to validate the suitability of these bio-composites as sustainable fuel options for decentralized blacksmithing operations and similar high-heat artisanal processes. By addressing both agricultural and

polymeric waste streams, the study not only contributes to the field of bioenergy but also supports broader goals in sustainable materials management and low-emission energy system design. The findings are expected to inform local energy policy, promote resource-efficient waste reuse, and stimulate interest in the development of small-scale biofuel technologies adaptable to informal manufacturing sectors in low- and middle-income countries.

II. Materials and Method

2.1 Materials and sample preparation

The primary biomass used in this study was rice husk (*Oryza sativa*). It was sourced from rice cultivation and processing site in Nenwe, within the Agwu-aninri Local Government Area of Enugu State, Nigeria. Rice husk, a by-product of post-harvest milling, was selected due to its high availability, combustion potential, and high silica content which contribute to its' structural and thermal resilience when subjected to torrefaction process. The synthetic component of the composite fuel was low-density polyethylene (LDPE) waste. It was sourced in the environment within the Federal University of Technology, Owerri, Imo State, Nigeria. LDPE was selected based on its high calorific value, softening behaviour, and resistance to moisture uptake, all of which enhance the performance of composite biofuels (Zhang et al., 2022; Zhao, Zhou, et al., 2022).

Both rice husk and LDPE waste were subjected to preparatory procedures aimed at standardizing particle size and eliminating moisture content to improve torrefaction uniformity and nugget consistency. The rice husk was sun-dried for 21 days to significantly lower its moisture content and prevent microbial degradation. Following drying, the husk was ground using a combination of an industrial grinder and a ball mill. The ground material was subsequently sieved to achieve a particle size of 30 mesh (496.7 µm), deemed optimal for densification and homogeneity. LDPE waste samples were thoroughly washed to eliminate residual contaminants and then dried using a dehumidifying machine. The dried LDPE was mechanically shredded into fine particles to facilitate even distribution during blending and improve melt-bonding during the torrefaction process. All prepared materials were stored in sealed air-tight containers prior to use to avoid moisture re-absorption.

2.2 Rice husk-LDPE waste nugget formulation

Fuel nugget samples were prepared using varying volumetric ratios of rice husk and LDPE waste. Five different formulations were developed to evaluate the effect of increasing polymeric content on the properties of the final product (as shown in Table 1). Each formulation was blended manually to ensure homogeneity before loading into the torrefaction system.

Table 1: Rice Husk-LDPE waste nugget Formulations

Sample ID	Rice Husk (% vol.)	LDPE (% vol.)	Total Composition (%)
A	100	0	100
B	80	20	100
C	60	40	100
D	40	60	100
E	20	80	100

2.3 Experimental Method

The torrefaction process was carried out using a custom-built torrefier developed by the Scientific Equipment Development Institute (SEDI), Enugu, Nigeria. The system includes a control panel, an electrically heated barrel containing a feed screw, and a die assembly for densifying the heated composite into fuel nuggets. The feedstock blend was introduced through a hopper and subjected to specific thermal and residence time conditions as shown in table 2. The torrefaction process involved controlled heating of the blended rice husk and LDPE waste under limited oxygen conditions. This procedure facilitates partial thermal degradation, reduces moisture and volatile matter, and increases fixed carbon content, thereby enhancing the composite's energy density and stability (Basu, 2010; Bridgeman et al., 2008). The experiments were conducted at two temperatures (250 °C,

and 300 °C) and two residence times (30 and 60 minutes), consistent with established research parameters (Ibrahim et al., 2013; Olugbade & Ojo, 2020). After the torrefaction, the nuggets were allowed to cool under ambient air. Each batch was labelled accordingly and stored in dry containers for subsequent characterization. The choice of torrefaction temperature and residence time was informed by the need to optimize fuel properties while minimizing mass and energy losses. Higher temperatures are known to enhance carbonization but may also increase brittleness and reduce structural integrity (Nhuchhen et al., 2014; Pentananunt et al., 1990). Thus, both moderate and high conditions were incorporated to examine the balance between combustion efficiency and mechanical durability. Additionally, previous findings have indicated that LDPE content significantly influences nugget integrity and calorific performance. Lower LDPE blends may suffer from insufficient binding, whereas excessively high polymer ratios may reduce biochar yield and elevate melting behaviour (Zhang et al., 2022). The selected formulation range allows for capturing these trade-offs across a continuum of biomass-to-plastic ratios.

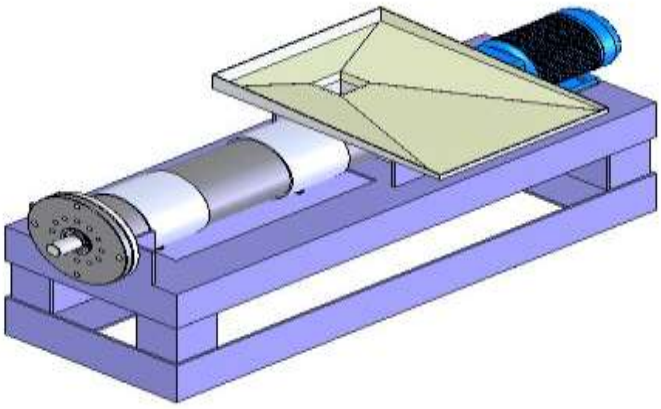

Fig. 1: Isometric view of developed Torrefaction Machine (Uche et al., 2025)

Table 2: Torrefaction Condition

Condition ID	Final Temperature (°C)	Residence Time (minutes)
250–30	250	30
250–60	250	60
300–30	300	30
300–60	300	60

2.3 Characterization of nugget samples

Proximate analysis included determination of moisture content, volatile matter, ash content, and fixed carbon content. Measurements were conducted using a Thermogravimetric Analyzer (TGA Q1600). This involved determining the moisture content (MC) by heating the samples under inert conditions and calculating the mass difference before and after drying using equation 1. Ash content (AC) was evaluated by subjecting the samples to combustion at temperatures ranging between 500 and 600 °C, with the residual mass used to compute ash concentration in accordance with equation 2. Volatile matter (VM) was assessed under controlled heating, and its value was obtained from weight loss data using equation 3. Fixed carbon content (FCC) was calculated by deducting the sum of ash and volatile matter from 100%, in line with the approach described by Mohalik et al., (2009) represented in equation 4. Finally, the calorific value (CV) of the samples, expressed in kcal/kg, was estimated based on the energy released during combustion using equation 5.

$$MC = \left[\frac{M_2 - M_3}{M_2 - M_1}\right] \text{ x } 100\% \quad (1)$$

$$AC = \left[\frac{(M_3 - M_1)}{(M_2 - M_1)}\right] \text{ x } 100 \text{ x } \left[\frac{100}{(100 - MC)}\right] \quad (2)$$

$$VM = \left[\frac{100(M_2 - M_3) - MC}{(M_2 - M_1)}\right] \text{ x } \left[\frac{100}{(100 - MC)}\right] \quad (3)$$

$$\%FCC = 100\% - (\%AC + \%VM) \quad (4)$$

$$CV = 7115.97 - 123.97 \text{ x } MC - 81.3121 \text{ x } AC + 20.7421 \text{ x } FCC \quad (5)$$

Where, MC = moisture content, AC = ash content, and FCC = fixed carbon content

The surface morphology structure analyses were done with a Keyence VH-8000 optical digital microscope and imaging was conducted under controlled magnification and digitally recorded. The flammability and combustion behaviour of the torrefied nuggets were evaluated through vertical flammability testing in accordance with ASTM standard (ASTM D641, 2020), wherein each sample was vertically mounted and exposed to a Bunsen burner flame for 10 seconds, with ignition time, self-extinguishing time, and glow duration duly recorded. Additionally, the burning rate was assessed following ASTM standard (ASTM D7140, 2018), by measuring the mass loss per unit time under standardized airflow conditions until complete combustion was achieved.

III. Results and Discussion

3.1 Physio-thermal changes of biomass fuels upon torrefaction

One noticeable change in torrefied biomass is the colour. Studies have shown that the colour changes to a more intense brown with higher torrefaction conditions, whether in temperature or increased residence time as reported (Bridgeman et al., 2010; Phanphanich & Mani, 2011). Figure 2 (a and b) display the changes in colour for rice husk biomass fuels torrefied rice husk-LDPE waste nuggets under various conditions. It is important to note that torrefaction and carbonization are two distinct thermal processes. The first noticeable transformation in torrefied biomass is the colour, which changes from brown to darker brown or black as the torrefaction temperature and residence time increase in line with other researchers (Aydemir et al., 2012; Olugbade & Ojo, 2020). The changes in colour upon torrefaction are mainly due to hydrolysis and oxidation reactions. The change in colour from light brown to dark brown, black, or red-orange depends on the type of phenolic compounds that form during torrefaction. Therefore, depending on the reaction time and temperature of the torrefaction process, the colour of the solid product changes from light brown to dark brown or black.

Fig. 2(a) Images of rice husk (A, B, C and D) and **(b)** rice husk- LDPE waste nugget sample

3.2 Surface morphology analysis of nugget samples

The change to the surface morphology of biomass particles upon torrefaction has a subsequent effect on their surface area. The morphology of the treated rice husk is shown in Figure 4 (a & b) respectively below. Torrefaction of rice husk-LDPE waste composites at 250 °C induces marked morphological transformations that

intensify with prolonged exposure. Micrographic analysis reveals that samples treated for 30 minutes exhibit initial fragmentation, moderate porosity, and uneven surfaces, indicative of early devolatilization and thermal stress within both the biomass and polymer matrices (Prins et al., 2006). These physical alterations correspond to the onset of structural degradation, including the formation of pores and fissures resulting from moisture loss and partial volatilization of light organics. The presence of mixed coloration and fiber-like surface features further confirms partial carbonization and non-uniform heat distribution (Van Krevelen & Te Nijenhuis, 2009).

In contrast, samples subjected to 60 minutes of torrefaction demonstrate more extensive mechanical breakdown, with deeper cracks, greater disintegration of particles, and significantly heightened porosity. This prolonged thermal exposure promotes the release of additional volatiles and accentuates the decomposition of both the lignocellulosic and polymer phases, resulting in a darker, more carbon-rich surface. Such changes suggest increased carbonization and a shift in chemical composition, with potential improvements in combustion reactivity and adsorption efficiency due to a substantially increased specific surface area (Liu et al., 2013). However, the brittleness of the material may also increase with prolonged torrefaction, potentially compromising mechanical stability in certain applications.

Surface micrographs (Fig. 4) reveal heterogeneous textures characterized by a combination of carbonized regions, fibrous residues from rice husk, and abundant pores. The presence of darker, denser zones suggests advanced thermal decomposition and partial carbonization of organic constituents, consistent with prior findings on biomass thermochemical transformation (Shen et al., 2014a).

The increase in porosity, particularly in the 60-minute samples, reflects the intensified devolatilization and structural breakdown of both biomass and polymer components. Prolonged exposure at elevated temperatures facilitates the cleavage of polymer chains in LDPE and the thermal degradation of hemicellulose, cellulose, and lignin in the rice husk matrix. This not only promotes the formation of additional voids and surface roughness but also leads to the release of volatile compounds, shrinkage, and eventual formation of char which is in line Shen and his team (Shen et al., 2014a).

The melting and partial redistribution of LDPE in longer-duration samples contribute to smoother surface areas while simultaneously enhancing carbon concentration, as evidenced by the darker appearance of the 60-minute samples. Such changes imply a trade-off between energy density and physical integrity; while porosity increases reactivity and reduces moisture retention, it also tends to lower bulk density and may diminish mechanical strength, stiffness, and structural cohesion.

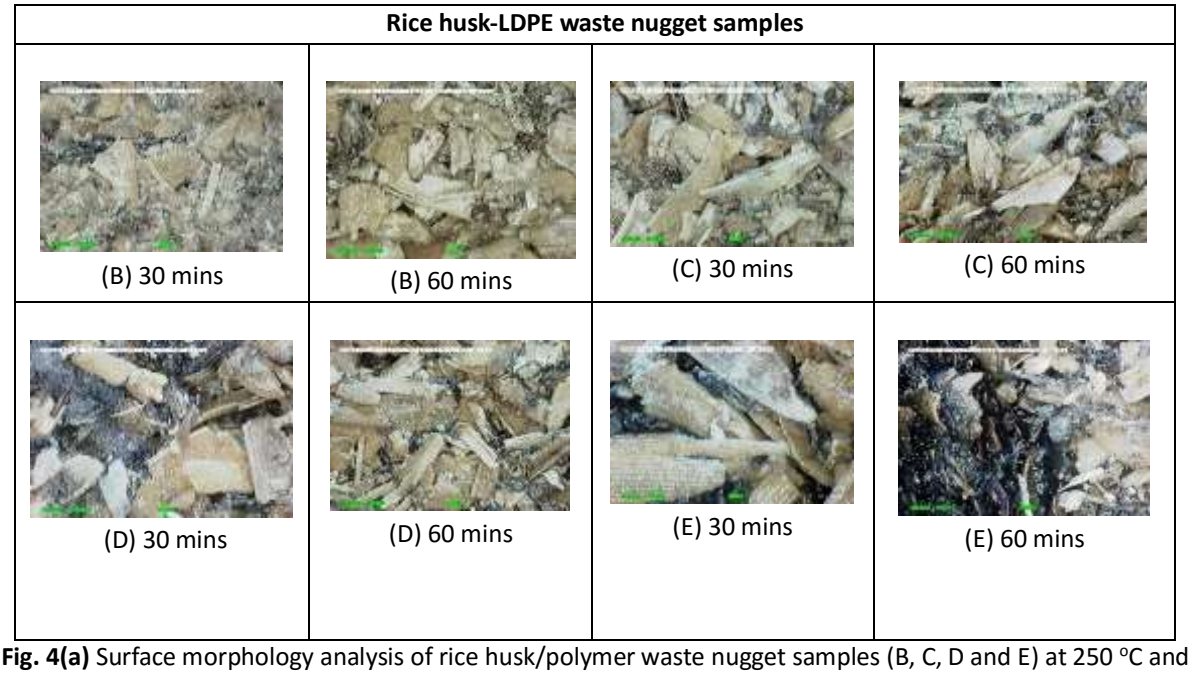

Fig. 4(a) Surface morphology analysis of rice husk/polymer waste nugget samples (B, C, D and E) at 250 °C and different time.

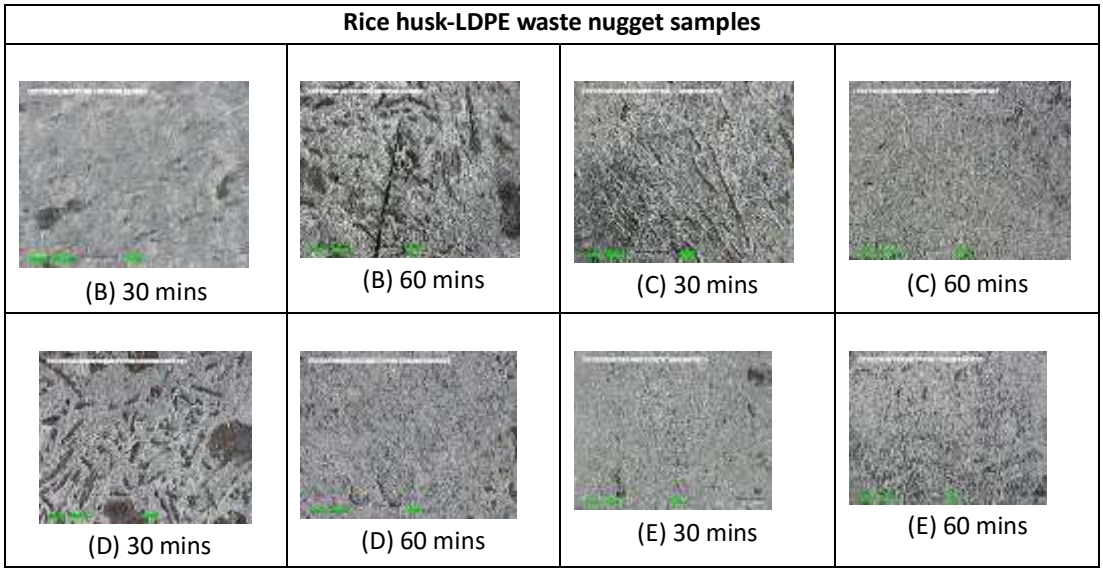

Fig. 4(b) Surface morphology analysis of rice husk/polymer waste nugget samples (B, C, D and E) at 300 ^{o}C and different time

3.3 Proximate Analysis of torrefied rice husk-LDPE waste nuggets

The results of proximate analyses of the following parameters (moisture content, ash content, fixed carbon content and calorific value) on torrefied rice husk and LDPE waste nugget samples produced at 250 °C for 30 mins and 60 mins respectively were presented as shown in Table 3. It was observed within temperature of 250 °C and resident time of 30 mins that moisture content decreased markedly from 6.40% to 2.43%, enhancing combustion efficiency by reducing energy loss during drying (Kumar et al., 2009; Tumuluru et al., 2021). Volatile matter (VM) declined significantly, particularly in samples C to E, reflecting improved thermal stability and reduced off-gassing risks (Yang et al., 2007). Ash content dropped from 11.46% in Sample A to 5.73% in Sample E, indicating reduced slagging potential and improved combustion performance (Vassilev & Vassileva, 2016). The fixed carbon content (FCC) rose from 79.20% to 92.35%, signifying enhanced energy retention and prolonged combustion suitability (Basu, 2010). Finally, the calorific value increased from 7,032.73 Kcal/kg to 8,264.13 Kcal/kg, confirming the improved energy density of the nuggets (Demirbaş, 2005).

For the case of temperature of 250 °C and resident time of 60 mins**,** moisture content decreased significantly to 1.49%, which improves combustion efficiency and energy yield by minimizing energy loss during drying (Bridgwater, 2012; Kumar et al., 2009). Volatile matter dropped to as low as 0.65%, indicating increased thermal stability and reduced emissions potential (Chen et al., 2015; Yang et al., 2007). Ash content also declined notably to 4.26%, reducing slagging risks and maintenance burdens (Demirbas, 2004; Vassilev et al., 2010). Fixed carbon content rose markedly to 94.27%, signifying a higher concentration of combustible matter suitable for sustained energy release (Basu, 2010; Kumar et al., 2009). Concurrently, the calorific value reached 8,539.45 Kcal/kg, reflecting greater energy density and improved fuel performance (Demirbaş, 2005). Overall, extended torrefaction residence time at moderate temperature effectively upgrades biomass-polymer composites into stable, efficient, and high-quality solid fuels, consistent with established findings in thermochemical biomass processing (Basu, 2010; Yang et al., 2007).

Table 3: Proximate analyses result on torrefied rice husk-LDPE waste nuggets at 250^{o}C under varying resident time.

Samples	Time (mins)	MC (%)	VM (%)	AC (%)	FCC (%)	CV (Kcal/Kg)
A		6.40	1.51	11.46	79.20	7,032.73
B		4.40	1.17	8.931	86.53	7,638.35
C	30	3.49	1.00	8.291	88.00	7,833.69
D		3.21	0.64	6.637	90.36	8,051.84

E		2.43	0.52	5.723	92.35	8,264.13
A		6.40	1.51	11.460	79.20	7,032.73
B		2.71	1.46	10.970	84.09	7,631.45
C	60	4.51	1.37	9.482	85.94	7,567.67
D		3.52	1.31	7.718	88.57	7,888.38
E		1.49	0.65	4.260	94.27	8,539.45

In addition, Table 4 presents the results of proximate analyses on torrefied rice husk and LDPE waste nugget samples produced at 300 °C for 30 mins and 60 mins respectively. It was observed at a torrefaction temperature of 300 °C for 30 minutes that moisture content dropped notably, with Sample D reaching as low as 0.79%, indicating efficient dehydration that enhances combustion efficiency and energy yield (Yang et al., 2007). Volatile matter remained low across all samples, with Sample D at 0.23%, reflecting enhanced thermal stability and storage safety (Basu, 2010). Fixed carbon content peaked at 98.95% in Sample B, supporting sustained heat release for prolonged combustion (Chen et al., 2015). Sample B also recorded the highest calorific value (8,463.36 Kcal/kg), underscoring improved energy density (Demirbas, 2004). However, ash content varied, with Sample D showing a high concentration (11.66%), potentially reducing its suitability due to slagging risks, while Sample B, with 3.81%, demonstrated more favourable combustion properties (Vassilev et al., 2010). These findings affirm the critical role of optimizing torrefaction parameters to achieve desirable biofuel characteristics for practical energy applications.

Furthermore, at a torrefaction temperature of 300 °C for 60 mins, moisture content dropped significantly (0.39–0.56% in Samples C–E), enhancing combustion efficiency and storage stability (Basu, 2018). Volatile matter was nearly eliminated (as low as 0.02% in Sample E), increasing thermal stability and reducing environmental emissions during combustion (Chen & Kuo, 2020). Fixed carbon content remained high across samples (up to 95.70% in Sample B), supporting sustained heat output and energy density (Singh et al., 2020). Calorific values peaked at 8,337.35 Kcal/kg in Sample E, affirming the fuel's viability for industrial applications (Gupta & Demirbas, 2010).

Ash content varied, with some samples (e.g., Sample C) experiencing elevated levels, suggesting mineral concentration due to prolonged exposure, which may pose operational challenges (Vassilev et al., 2010). However, the integration of LDPE waste generally contributed to lower ash content, increased fixed carbon retention, and higher energy values compared to pure rice husk, which had higher moisture (6.40%), volatile matter (1.51%), and ash (11.46%) and a lower heating value of 7,032.73 Kcal/kg. These outcomes confirm that co-torrefaction of biomass with LDPE, under optimized temperature and residence time, substantially enhances the biofuel's combustion characteristics and environmental sustainability (Chen et al., 2015; Demirbas, 2004).

Table 4: Proximate analyses results on torrefied rice husk-LDPE waste nuggets at 300^{o}C under varying resident time

Samples	Time (mins)	MC (%)	VM (%)	AC (%)	FCC (%)	CV (Kcal/Kg)
A		6.40	1.51	11.46	79.20	7,032.73
B		3.18	0.28	3.813	98.95	8,463.36
C	30	1.28	0.88	6.689	93.59	8,353.87
D		0.79	0.23	11.660	87.91	7,892.60
E		1.79	0.44	8.074	90.11	8,105.85
A		6.40	1.51	11.46	79.20	7,032.73
B		2.11	0.83	4.634	95.70	8,461.84
C	60	0.56	0.19	8.673	90.81	8,224.14
D		0.43	0.04	8.780	90.62	8,245.62
E		0.39	0.02	7.619	91.12	8,337.35

3.4 Flammability test

Torrefied rice husk-LDPE waste nugget samples produced at 250 °C under the resident of 30 and 60 mins respectively were not recorded because no significant physical nuggets formed during torrefaction. The flammability results of torrefied rice husk-LDPE waste nuggets at 300 °C for 30 and 60 mins respectively as seen in Table 5 below reveal consistent improvements in combustion characteristics across all samples. Ignition times were generally low, with Samples C and D igniting in as little as 2 secs, indicating high fuel reactivity and ease of ignition. Extinguishing times were prolonged up to 365 secs in Sample D, demonstrating strong combustion persistence, which is favourable for energy-intensive applications such as blacksmithing (Zhao et al., 2022). Glow times, a measure of residual thermal activity, decreased with longer residence times, suggesting increased thermal stabilization and reduced post-flame reactivity (Zhao et al., 2022). All samples successfully ignited the cotton indicator, affirming high flame intensity and thermal output.

It was observed that 60 mins torrefaction condition generally led to longer extinguishing times and lower glow durations, indicative of improved char consolidation and carbonization (Liu et al., 2013). These outcomes confirm that extended thermal treatment enhances the structural and energy performance of biomass–polymer composites, aligning with prior studies on torrefaction's role in producing stable, energy-dense biofuels (Basu, 2018; Chen & Kuo, 2020). It can therefore be said that sample E (300°C, 60 min) offers the best balance of ignition reliability, sustained burn, and heat stability, making it the most appropriate candidate for blacksmithing applications where continuous high-temperature output is essential (Basu, 2010; Demirbaş, 2005; Shen et al., 2014b).

Table 5: Flammability test of torrefied rice husk- LDPE waste nugget samples produced at 300 °C resident time of 30 and 60 mins respectively

Sample ID	Ignition time (sec)	Ignition time (sec)	Extinguishing time (sec)	Extinguishing time (sec)	Glow time (sec)	Glow time (sec)	Cotton indicator ignited	Cotton indicator ignited
	30 mins	60 mins	30 mins	60 mins	30 mins	60 mins	30 mins	60 mins
B	5	3	303	279	3	5	Yes	Yes
C	2	2	257	290	10	3	Yes	Yes
D	2	2	365	300	40	4	Yes	Yes
E	10	9	306	330	60	17	Yes	Yes

IV. Conclusion

This study examined the torrefaction and composite formulation of rice husk with low-density polyethylene (LDPE) waste to generate solid biofuel nuggets, yielding several important findings. The torrefaction process significantly enhanced the thermal properties of rice husk by lowering moisture and volatile substances, increasing fixed carbon content, and improving calorific value. The addition of LDPE waste as a binder not only strengthened the mechanical stability of the nuggets but also provided additional hydrocarbon energy, resulting in a denser and more efficient fuel product. Morphological analysis showed that longer torrefaction times at higher temperatures (especially 300 °C for 60 minutes) encouraged pore formation and partial carbonization, improving reactivity while presenting potential issues with nugget brittleness and ash behavior due to the silica content inherent in the husk.

With biomass valorization and the transformation of waste into energy, these findings are both timely and significant. revealing that agricultural residues and plastic waste can be effectively combined to create a hybrid bio-composite nugget fuel addressing the dual challenges of energy security and environmental issues arising from waste accumulation and dependence on fossil fuels.

The rice husk-LDPE waste nuggets offer a credible alternative for decentralized thermal energy and localized industrial fuel use. To support broader application and technological advancement, further studies should aim to optimize the biomass-to-polymer blend, characterize emission profiles during combustion, develop strategies for ash utilization, and engineer torrefaction systems suitable for continuous, scalable processing.

Conclusively, torrefied husk-LDPE waste nuggets represent a viable and effective approach to solid biofuel production. Their application holds particular value for regions seeking cost-effective, locally sourced alternatives to fossil fuels.

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