



Article Info

Received: 27th April 2025Revised: 20th July 2025Accepted: 21st July 2025

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Cite this: *CaJoST*, 2025, 2, 311-317

Design and Testing of Plastic Waste Torrefaction Reactor for Improved Torr Gas Production

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The growing demand for sustainable and renewable energy sources has sparked research into biomass torrefaction as a potential alternative to fossil fuels. This paper discusses the design and construction of a compact high-density polyethylene (HDPE) flakes torrefaction reactor that utilises charcoal and liquefied petroleum gas (LPG) as the primary heat source. The reactor system comprises a jacket, flange, convergence cone, charcoal tray, condensing and gas extraction unit, blower, and angular steel frame. The reactor, built from 3mm-thick mild steel, has a system that uses a blower to circulate hot air, making the process of heating HDPE flakes for torr gas more efficient. The gas outlet unit was equipped with a continuous water circulation system for efficient cooling and ease of gas compression and condensation into a cylinder. The experimental phase involved waste bottle preparation to flakes, size standardisation, temperature management, moisture extraction, low-energy density, product properties, and comparison with traditional fossil fuels. The torrefaction process produced a syngas mixture called torr gas that was compressed into a cylinder with the aid of a compressor for domestic use as fuel. Torrefied gas improves fuel quality, reduces greenhouse gas emissions (GHGE) and energy density by 30-40%, reduces moisture, and offers faster burning rates, efficient energy release, and cleaner torr gas combustion.

Keywords: Renewable energy, biomass torrefaction, reactor, charcoal and torr gas

1. Introduction

The global energy demand is on the rise due to rapid industrialization, urbanisation, population growth, and increased waste generation, necessitating urgent attention to meet human social and economic needs (Hofstetter and Kovalchuk, 2021). The challenge of ensuring reliable energy supplies, promoting proper waste management ethics, and addressing climate change remains one of humanity's most significant challenges (Cao et al., 2014). Global energy production, primarily fueled by fossil fuels, coal, oil, and natural gas, has significantly contributed to environmental degradation and climate change (Asumadu-Sarkodie & Owusu, 2016a). The burning of fossil fuels and plastic waste has led to a rise in greenhouse gas emissions, posing a threat to global warming and ecological balance. Over 75% of GHG emissions and 90% of CO₂ output come from fossil fuels, leading to unsustainable practices like depleting finite reserves, destabilising ecosystems, and escalating geopolitical conflicts. The shift towards cleaner, more sustainable energy sources and environmentally friendly solutions has become a critical necessity (Zhang et al., 2021).

Renewable energy sources like bioenergy, solar, wind, geothermal, hydropower, and ocean energy provide sustainable alternatives to fossil fuels, emitting minimal greenhouse gases and empowering communities (Lu et al., 2015). The UN's Sustainable Development Goals emphasise climate action, affordable clean energy, and environmental sustainability, yet renewables only account for 4% of global energy consumption. The increasing focus on sustainability and renewable energy has sparked a renewed interest in biomass, which plays a crucial role in energy security, waste management, and transitioning to carbon-neutral energy. López et al. (2021) suggest that biomass energy can help reduce climate change by reducing greenhouse gas emissions and replacing fossil fuels, promoting a more sustainable future (Acharjee and Brown, 2016). Renewable energy sources are crucial for energy security and climate change mitigation, with estimating that 90% global electricity could be generated from these sources by 2050. Transitioning to renewable energy is crucial for reducing greenhouse gas (GHG) emissions and achieving energy independence, especially in fossil

fuel-importing nations where 80% of the world's population lives. Biomass energy, a viable renewable source, significantly contributes to sustainable development by offering energy access, economic growth, and environmental conservation opportunities (Yang and Chen, 2018). Biomass, a renewable energy source, contributes 10-14% of the global energy supply, derived from organic materials like wood, agricultural residues, and municipal waste. The issue is especially relevant in rural areas, where 1.4 billion people lack electricity access and 85% rely on traditional biomass for energy (Abbasi and Abbasi, 2010). Transitioning from conventional biomass to refined, energy-dense forms is crucial for improving energy access, reducing deforestation, and minimising environmental impacts through combustion, gasification (Bridgwater, 2012), anaerobic digestion, and torrefaction. Biomass energy is a renewable energy source that offers numerous benefits, including its potential as a renewable resource, waste management (López *et al.*, 2021), carbon neutrality and energy diversification enhancing energy independence and stability. Raw biomass faces limitations like low energy density, high moisture content, and hygroscopicity, requiring pretreatment processes to improve efficiency, storage, and transport as a coal alternative.

Torrefaction is a thermal pretreatment process that improves biomass's physical and chemical properties by heating it in an oxygen-deficient environment, removing moisture and volatile organic compounds. Torrefied biomass, a solid product with higher energy density, improved combustion properties, and better storage stability, is produced through this process (Bridgwater, 2012; Bridgeman *et al.*, 2018). Torrefied biomass is a promising power generation alternative due to its hydrophobic properties, higher carbon content, and ease of handling. Torrefaction has various applications, such as biomass upgrading, co-firing with Coal (Zheng *et al.*, 2016), production of biofuels (Müller *et al.*, 2019), and industrial applications like cement production and metallurgy, where high temperatures are required (Bhatia *et al.*, 2016). Sustainable energy solutions aim to improve energy security and encourage the utilisation of renewable resources. Research has optimised torrefaction processes and reactor designs to enhance efficiency and economic viability, with studies showing torrefaction increases biomass energy output, making it comparable to coal. Torrefaction, a process that reduces transportation and storage costs of biomass, is widely used in fixed-bed reactors, which involve controlled heating in a stationary bed. The identified challenges, including non-uniform heat distribution and high energy consumption, necessitate further research into reactor optimisation (Chen *et al.*, 2015). Figures 1 and 2 illustrate various physicochemical transformations within biomass during torrefaction and product outcome.

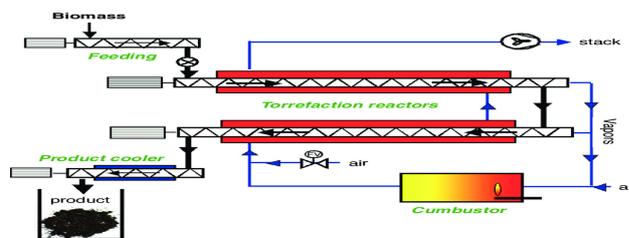


Figure 1: Schematic of a torrefaction process (Huang and Wang, 2016)

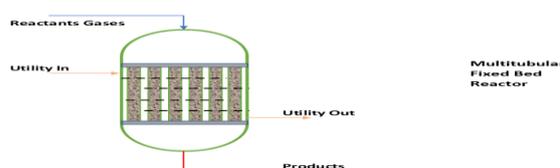


Figure 2: Fixed bed reactor (Mehra, 2021)

The efficient utilisation of biomass energy is hindered by issues like inconsistent feedstock quality, high processing costs, and technological limitations, necessitating the development of improved torrefaction techniques and reactor designs (Chen *et al.*, 2015). Torrefaction parameters can improve biomass quality and energy output, with advances in reactor technology facilitating large-scale adoption and ensuring a steady supply of high-quality solid biofuels. The study focuses on developing a fixed-bed waste bottle torrefaction reactor for producing high-quality syngas, offering an efficient, practical, and scalable biomass conversion technology as an alternative to conventional fuels. This will tackle global energy issues by offering a sustainable, cost-effective alternative to fossil fuels, mitigating climate change impacts, and being beneficial for home utilities.

2. Materials and Methods

The study aims to design, construct, and assess a fixed-bed biomass torrefaction reactor for enhanced energy density and combustion properties in biofuel production. Torrefaction is a thermal process that converts biomass into energy-dense, efficient biofuel by heating it to a specific temperature range of 200°C to 300°C in an inert atmosphere. It removes moisture and volatile organic compounds from biomass, enhancing its energy density, handling, and storage properties (Bhatia *et al.*, 2016). A fixed bed reactor is utilized in torrefaction processes, where biomass is placed in a stationary bed and heat is supplied from the reactor walls or inert gas flow. Fixed Bed Reactors offer several advantages, such as temperature uniformity (Acharjee *et al.*, 2016), simplicity and cost-effectiveness (Fang *et al.*, 2018), scalability (Bhatia *et al.*, 2016), enhanced product quality (Yang *et al.*, 2018).

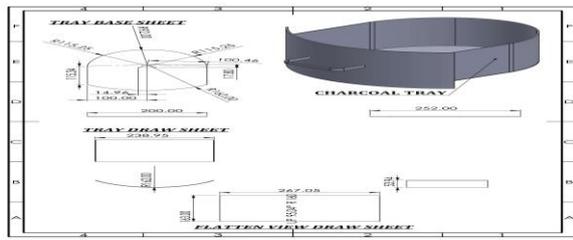


Figure h: Tray sheet view

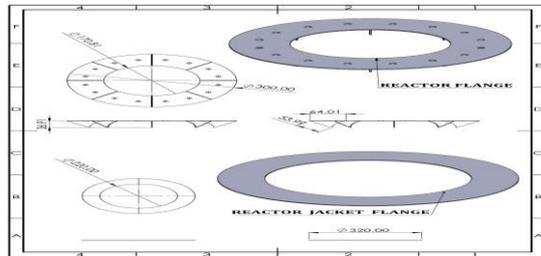


Figure 3i: Reactor jacket flange

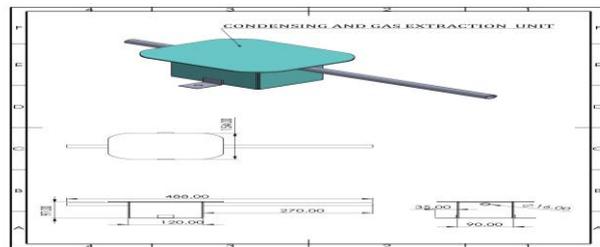


Figure 3j: Reactor condensing and gas extraction unit

2.2 Cutting, Shaping, and Surface Finishing

The reactor's geometric specifications were achieved through precise cutting and shaping during the fabrication process. A mild steel sheet was cut into trapezoidal and conical shapes, then welded using a Stonebridge Grade 12 electrode. Circular flanges were made from 3mm mild steel plates, with M8 bolt holes drilled. Stainless steel pipes, measuring 16mm in diameter, were cut to a length of 210mm for gas inlet and deburred using a grinding wheel. The cut edges were smoothed with 80-grit sandpaper to remove sharp burrs, and the welded joints were ground flush for seamless connections. Table 1 presents the components of the biomass torrefaction reactor.

Table 1: Design specification of the components

Item	Component	Specification	Description	Quantity
1	Reactor Jacket	305mm Θ x 400mmH Thickness, t = 1.5mm	Carbon Steel (anti-rust coated)	1
2	Reactor	280mm Θ x 210mmHeight, H; t = 1.5mm	Carbon Steel (anti-rust coated)	1
3	Reactor flange	16 holes, 3mm Θ	Mild Steel (3mm)	1

4	Reactor Jacket Flange	16 holes, 3mm Θ	Mild Steel (3mm)	1
5	Reactor Converging Cone	ID = 180, OD = 350, H = 200	Mild Steel (3mm)	1
6	Condensing and Gas Extraction Unit	100mm x 100mm x 200mm deep	Mild Steel (3mm)	1
7	Charcoal Tray	205mm x 260mm	Carbon Steel (anti rust coated)	1
8	Charcoal Tray Container	280mm Θ x 170mmH t = 1.2mm	Carbon Steel (anti rust coated)	1
9	Blower	12V DC	12V DC Brushless Blower	1
10	Frame	650mm x 400mm	Mild Steel	1

2.3 Welding and Assembly

The reactor's structural integrity was ensured through high-quality welding and systematic assembly using a Shielded Metal Arc Welding (SMAW) machine, continuous bead welding for critical joints, and quality control through visual inspection and reinforcement. The reactor-jacket system consists of a carbon steel reactor body nested inside an outer drum, with a 25mm annular gap for insulation. Mild steel chambers and condensed and non-condensable gas pipes are welded to the reactor outlet. A carbon steel drum serves as the power source, and a 12V DC brushless blower is secured to the charcoal tray inlet. A modified burner was integrated into a reactor base, tested for leaks using nitrogen gas and soap solution, and coated with rust-protective spray paint.

2.4 Working Principles of the Biomass Torrefaction Reactor

The process begins with preparing HDPE plastic waste as the biomass feedstock. The plastic bottles are cleaned, shredded, and cut into uniform flakes for consistent heat distribution during torrefaction, preventing uneven heating and ensuring efficient thermal decomposition. Four samples (A, B, C and D) of HDPE flakes are loaded into the reactor chamber's fixed bed for torrefaction, sealed using a flange system to maintain an oxygen-limited environment for controlled thermal treatment as presented in Figure 4. The reactor uses a dual heating system for temperature control. The primary source is charcoal-based heating, where charcoal is burned in a tray, and a 12V DC blower regulates combustion intensity. The secondary source is a gas burner, which supplements heat when higher

temperatures are needed. The torrefaction process involves HDPE decomposing in an oxygen-starved environment, breaking down into volatile gases and a carbon-rich solid residue. The process uses infrared thermometers to control temperature and handle gases, with condensable liquefying into bio-oil analogues and non-condensable gases venting or capturing for further use. The reactor's performance is monitored using an infrared thermometer and data logger, ensuring uniform heat distribution and correlation with external surface measurements, by heating to target torrefaction temperatures and opening the lid at 10-minute intervals. The torrefied HDPE is extracted from a fixed bed, weighed to determine mass yield, and analyzed for calorific value, moisture content, and combustion properties. The biogas yield was compressed into a gas cylinder and tested for combustion as showed in Figure 5.



Figure 4: HDPE torrefaction reactor



Figure 5: Torr gas test

2.5 System Performance Evaluation

The process involves plotting internal and external temperatures (T_i and T_e) to create a regression equation 1.

$$T_i = 1.2T_e + 25 \quad (1)$$

Data validation entails calculating the interior temperatures from external data. A linear correlation ($R^2 > 0.95$) for real-time internal temperature monitoring via external observations was noted. The technique entails lowering the moisture content of HDPE flakes by weighing 100 g of raw materials (W_i). The pre-torrefaction treatment lasted 60 minutes at 250°C, followed by weighing the cool torrefied HDPE in a desiccator (W_f). The percentage moisture loss (M_L) was determined using equation 2.

$$M_L = \frac{w_i - w_f}{w_i} \times 100 \quad (2)$$

The expected outcome is mass loss primarily from volatile release, with a 5-10% reduction due to polymer breakdown, rather than moisture. The process involved using a bomb calorimeter to test the calorific value of raw and torrefied HDPE. The objective of improving the high heating value (HHV_{imp}) is obtained from equation 3.

$$HHV_{\text{improved}} = \frac{HHV_t - HHV_r}{HHV_r} \times 100 \quad (3)$$

The process involves torrefaction of 1 kg of raw HDPE (w_r), weighing cooled torrefied HDPE (w_t), and calculating mass yield (Y). The outcome involved the conversion of HDPE raw material (46 MJ/kg) to the torred HDPE (48–50 MJ/kg) with a moderate HHV increase due to reduced volatiles and densified carbon structure as obtained from equation 4.

$$Y = \frac{W_t}{W_r} \times 100 \quad (4)$$

The raw HDPE weight is 1000 g, and the final weight is 750 g, having a moisture loss percentage of 25%. The expected outcome is a high mass yield of over 85% due to HDPE's low moisture/ash content ($W_r = 1000$ g, $W_t = 900$ g). The heat transfer efficiency (η) was evaluated by comparing the energy input from the blower with the energy needed to maintain the desired reactor temperature, using equation 5.

$$\eta = \frac{E_u}{E_i} \times 100 \quad (5)$$

Where; E_u and E_i are energy utilized for heating and total energy input.

3. Results and Discussion

The reactor was kept within the intended temperature range of 250°C to 300°C, and temperature was measured on a regular basis with infrared thermometers. The greatest temperature was recorded at 280°C for 15 minutes of heating, while the lowest was 270°C for 45 minutes of torrefaction. Converting raw HDPE to syngas takes 60 minutes. The temperature-time profile of the reactor is shown in Figure 6. The reactor maintained a steady temperature of 275°C with slight fluctuations of $\pm 5^\circ\text{C}$, suggesting future insulating improvements. Figure 7 shows that the percentage moisture loss for the different evaluated HDPE samples (A-D) was 25%, 30%, 20%, and 28%, respectively.

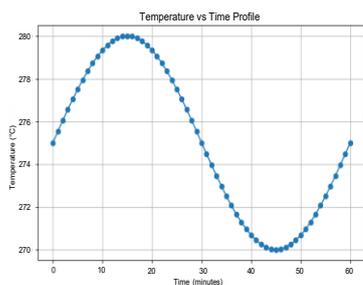


Figure 6: Temperature-Time profile of the reactor

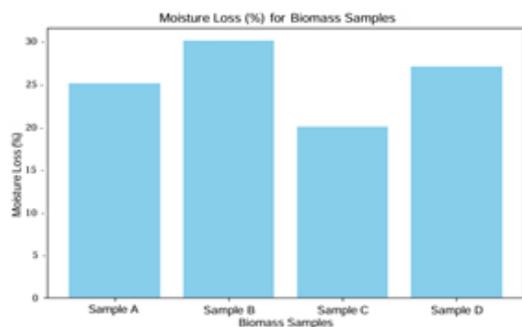


Figure 7: Percentage moisture loss of different HDPE samples

3.1 Heat Transfer Efficiency

The reactor used 500 kJ to maintain the target temperature, while the blower provided 600 kJ. Table presented the heat transfer data observed in course of the system performance evaluation. The average resulting heat transfer efficiency was obtained as 55%.

Table 2: Heat transfer data

S/N	Heating energy (kJ)	Total energy input (kJ)	Heat transfer efficiency (%)
1	330	600	55.0
2	340	620	54.8
3	320	580	55.2
4	350	640	54.7
5	335	610	54.9
6	345	630	54.8

3.2 Calorific Value Improvement

Table 3 presented the calorific values comparison between raw and torrefied HDPE samples. Torrefied HDPE flakes showed a 15-20% increase in heating value (HHV) compared to raw HDPE, resulting in an improvement of approximately 16.7%.

Table 3: Calorific value content

Sample Type	HHV (MJ/kg)	Improvement(%)
Raw Biomass	18	0
Torrefied Biomass	21	16.7

3.3 Product Characterization

3.3.1 Physical and Chemical Properties

The torrefied biomass showed a significant increase in carbon content from 42% to 55%, accompanied by a reduction in oxygen and volatile matter, as per standard elemental analysis techniques. Post-torrefaction, HDPE densification was confirmed by increased bulk density and improved size, resulting in reduced energy consumption and enhanced stability against moisture reabsorption during storage.

3.3.2 Ignition Temperature and Burning Rate

As presented in Figure 8, combustion tests showed torrefied HDPE ignited at a lower temperature 230°C than raw HDPE, indicating improved combustion properties and a higher burning rate, indicating faster energy release.

3.3.3 Emission Analysis

Emission tests showed reduced concentrations of unburned hydrocarbons and particulates from torrefied HDPE, indicating cleaner combustion due to reduced volatile matter.

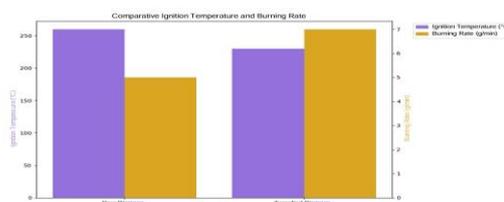


Figure 8: Elemental composition of HDPE after torrefaction

3.3.4 Solid Fuel Yield

The mass yield of 1000 g of raw HDPE and 350 g of torrefied HDPE was 35%. The test results showed a consistent mass yield of 30%-40% of syngas produced. This indicates that a small portion of raw HDPE is converted into a stable, energy-dense solid fuel through the use of an air condenser.

3.3.5 Fuel Quality and Efficiency

The solid fuel yield is crucial for evaluating the efficiency of the torrefaction process. A higher mass yield indicates more HDPE is retained as usable fuel, enhancing its economic viability. The torrefied HDPE has increased energy density, improved combustion properties, and enhanced storage stability. The hydrophobic nature of the fuel enhances storage stability, despite the inherent loss of mass during processing. The fixed-bed reactor's torrefaction process significantly improves fuel quality. It reduces moisture content, improves energy density, enhances calorific value, and improves combustion characteristics.

4. Conclusion

The study evaluated a fixed-bed HDPE torrefaction reactor for producing high-quality torr gas, demonstrating consistent temperature maintenance within the target range of 250°C to 300°C with minor deviations. The reactor, made of 3mm-thick mild steel, uses a blower to circulate hot air for heating HDPE flakes for torr gas. It features a continuous water circulation system for efficient cooling and gas compression. The torrefaction produces torr gas for domestic fuel. The study highlights the significance of temperature control in torrefaction, revealing a preliminary 55% efficiency, which reduces moisture content, enhances energy density, and improves fuel stability. Torrefied HDPE, a sustainable and environmentally friendly energy source, offers a 15-20% increase in calorific value, a lower ignition point, higher burning rates, cleaner combustion, and reduced emissions but a low mass yield due to moisture and volatile matter removal. The economically viable process retains rawer HDPE as fuel but requires improvements in reactor insulation, heat distribution, and a water-cooling condenser for better HDPE condensation.

Acknowledgements

Authors appreciate the contributions and efforts of all technologists at the workshop, department of Mechanical Engineering, Yaba College of Technology Lagos, Nigeria for the success of the work.

Conflict of Interest

The authors declare no conflict of interest.

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