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Review

A review of technoeconomic benefits of torrefaction pretreatment technology and application in torrefying sawdust

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Abstract: Economic analysis of the torrefaction process centers on the assessment of the economic feasibility of the production and utilization of torrefied biomass using developed models such as costs of biomass, electricity, labour, investment, transportation, etc. to evaluate the cost of biomass torrefaction. The increase in energy usage over the past century has raised concern over the energy insecurity and environmental unsustainability of current fossil fuel utilization; therefore, there is a need for energy diversification. An attractive alternative is biomass. However, the poor performance of raw biomass in energy generation further necessitates the development of refined technologies to enhance its performance, particularly at low temperatures between 200–300 °C. This study therefore reviews the technoeconomic benefits of torrefaction technology and reactors and their application in the pretreatment of sawdust. An overview of torrefaction technology, torrefied product characteristics, economic analysis of torrefaction reactors, and torrefaction cost/ton were reviewed. From the review, torrefaction significantly improved the physical, combustion, and performance characteristics of torrefied products, with comparable durability and storability to raw biomass. Compared with other thermal pretreatment methods, torrefaction is an economical way of improving biomass properties.

Keywords: technoeconomic; torrefaction; reactors; sawdust; pretreatment

1. Introduction

Energy plays a pivotal role in the development of any nation, so much so that the extent of energy development is a direct indication of the extent of economic development of a nation. Conventionally, fossil fuels are the primary energy source for most applications. However, the degrading consequences of fossil fuel exploitation and consumption, increased emissions of greenhouse gases (GHGs), and accelerated climate change have made fossil fuels less popular in recent years [1]. The increase in energy usage over the past century has raised concern over the sustainability of current fossil fuel consumption rates. The current trends in energy insecurity and environmental unsustainability can be addressed through energy resource diversification. Thus, the recent drive in the production of viable energy alternatives from biomass sources and low-carbon fuels is being promoted by the Renewable Fuel Standard (RFS) passed in 2005 [2]. The RFS promotes increased renewable fuel development to reduce overdependence on imported refined petroleum and greenhouse gas emissions [3].

An estimated two-thirds of the annual global biomass supply from different sources goes into household cooking, mostly in developing nations [4]. Apart from fuelwood, the global biomass resources largely revolve around fossil fuels [5,6] and wastes generated from agricultural residues or dedicated energy crops and forestry residues, particularly mill residues from woody biomass and sawdust [7]. Sawdust is a waste product of the secondary wood conversion process that is massively produced from wood processing industries and is available in large volumes globally, constituting environmental hazards due to its poor handling through indiscriminate open burning and dumping in mill sites and landfills.

Despite the advantages of biomass, there are restrictions on its use as the primary feedstock for energy production. Such restrictions are due to luminous yellow flames, excessive moisture contents, poor energy per unit volume, hydrophilic properties, high oxygen contents, and high levels of smoke generation above acceptable levels for household use [1]. These constraints limit their conversion and replacement as fossil fuels for energy production [2]. Consequently, these products are processed into valuable products for energy applications, as reported in the literature [8]. **Figure 1** provides an overview of the biomass (typically below 50% moisture content) processing system before pretreatment [9].

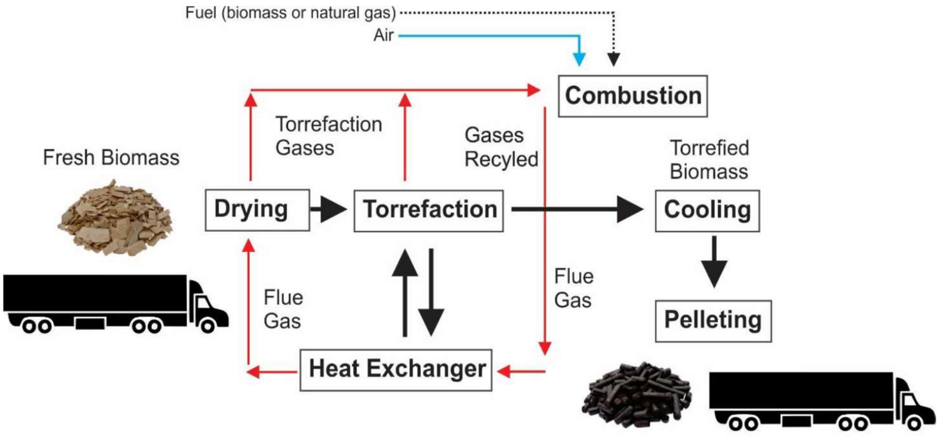


Figure 1. Torrefied pellets processing flowchart [10].

Sawdust preheating before densification is a suitable option for producing a higher-quality feedstock for a given energy input to reduce power consumption during the densification process [11,12]. This material process could equally increase the production rate, up to 340 to 360 kg/hr [13]. Kpalo et al. [14] revealed the concept of preheating feedstock material in a screw press to study its effect on energy savings. The result showed a total average energy saving of about 10.2% (23.5% at the heater and 10.8% at the motor).

Preheating or thermal pretreatment biomaterials to 200–250 °C before densification reduces compression and extrusion pressures by a factor of two, while a pressure reduction of 2.5–3.0 × 10^4 kN/m^2 with preheating is compared to an approximate pressure of 1.8 × 10^5 kN/m^2 without preheating. Pretreatment of sawdust before briquetting removes the volatile matter contents of the material, thereby improving its physical, mechanical, and combustion properties [15,16]. Pretreatment of lignocellulosic (biomass) materials before densification is an important age-long biomass-to-fuel conversion process for loosening or delignification of the compacted biomass structures to expose the cellulose fiber [17–19]. During this process, lignin, cellulose, and hemicellulose undergo chemo-structural changes to overcome the resistance provided by the cell wall [20]. Due to its impact on technical, economic, and environmental systems, biomass pretreatment has drawn significant study attention worldwide [21,22].

To speed up substrate hydrolysis, various pretreatment techniques, including torrefaction, have been described in the literature [16,23,24]. Biomass pretreatment through torrefaction has been recognized as a more attractive and less expensive process for sawdust pretreatment [17,25,26], and an appropriate practical method for commercial and household heating applications [25,26]. **Figure 2** shows the various thermal conversion processes, routes, and their potential high-value by-products. The extent of heat conversion conditions determines the makeup of the final products. This study therefore seeks to review the technoeconomic benefits of torrefaction technology and reactors in the pretreatment of sawdust.

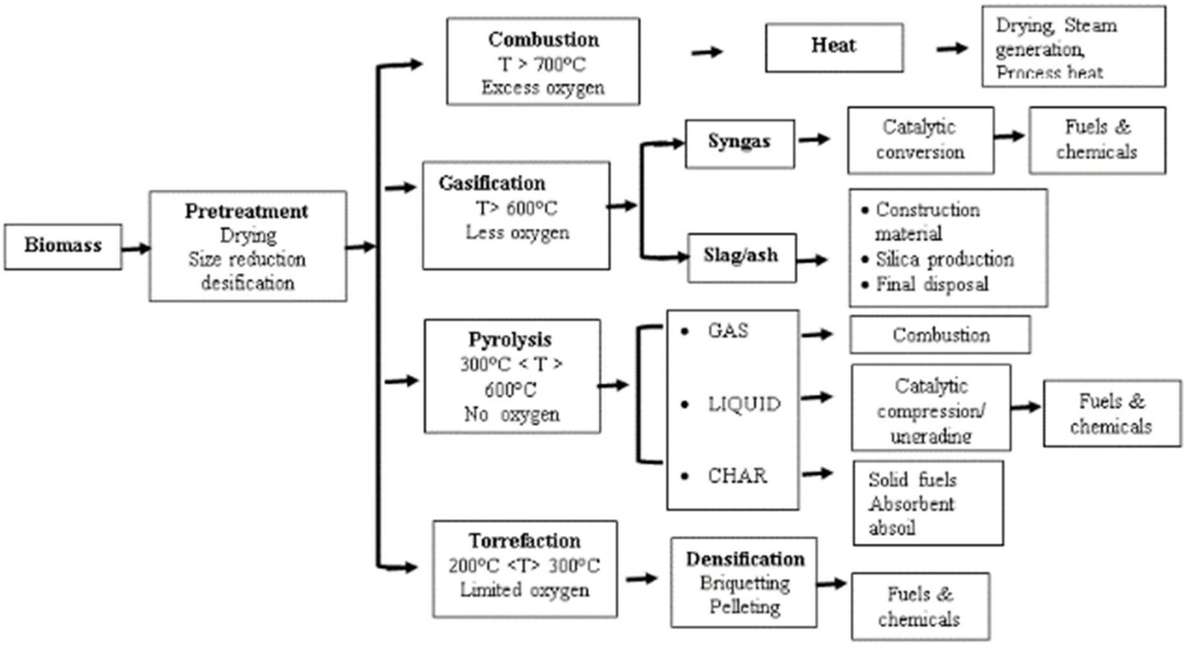


Figure 2. Biomass thermal conversion processes [27].

2. Methodology

Two methodologies employed in this work include a theoretical review of the works of reputable scholars and an analysis of torrefaction experiments, while the second methodology employs the empirical work of a developed laboratory batch reactor to torrefy the sawdust of Gmelina arborea *and* evaluate its products and economic viability.

2.1. Review of the torrefaction (semi-carbonation) process

Torrefaction technology was first investigated in the laboratory in the 1930s in France [28] and was derived from the French word for roasting [29]. In the last two decades, there have been renewed increases in interest in torrefaction as a potential feedstock pretreatment option [30,31]. Torrefaction is the roasting of feedstock in a near-inert (oxygen-free environment) atmosphere between 200–300 °C to increase the heating value, hydrophobicity, and combustion characteristics [25,26]. AMPC [32] and Szufa et al. [33] described torrefaction as ‘mild pyrolysis’ characterized by slow heating rates (typically <50 °C/min), relatively long residence times (30 to 90 min) and temperatures of 200 °C to 320 °C under atmospheric pressures [34,35]. There are several research works on torrefaction of other biomass: Ramos-Carmona et al. [36] reported on patula pine [37] at 200 °C–300 °C and 30 min of residence time; Bridgeman et al. [38] torrefied wheat straw and willow; Bello et al. [15] torrefied Gmelina arborea, among others.

Torrefaction requires that feedstock be subjected to a slow heating process in an oxygen-deficit environment at a temperature range of 200–300 °C in a near oxygen-free environment [16,39]. Several research studies have further established biomass torrefaction at these temperatures [34,40–42]. Prior to torrefaction, the biomass was heated at less than 50 °C per minute up to 105 °C, to evaporate the free water within the biomass to <10% moisture content. Drying processes take place at a non-reactive drying zone of 160 °C with material moisture released and most of the bond water removed at 160–200 °C.

Degradation of hemicellulose occurred at 180 °C, while thermal decomposition, devolatilization, and carbonization reactions occurred at between 200–270 °C, during which the biomass thermally decomposed to release moisture, volatile gases, and low energy compounds with colour change from yellow to brown [43]. These colour changes were reportedly dependent on temperature, residence time, heating rate, biomass type, initial moisture, particle size, and shape of biomass. Around 280 °C, torrefaction becomes entirely exothermic, with increased gas production, leading to the synthesis of extraneous gases and other weighty products [44,45].

During this process, near 100% of the moisture is eliminated, yet 90% of the energy content of the solid uniform product is preserved; about 70% of its dry weight mass remains [28], while hemicellulose materials are volatilized. The resulting torrefied solid component significantly differs in physical and chemical properties from the original biomass. These products possess hydrophobic characteristics, high energy density, and durable biodegradation [46]. Tumuluru et al. [44] gave a comprehensive review of the physical properties of torrefied products, such as density, grindability, pelletability, hydrophobicity, and storage behaviour in terms of off-gassing, spontaneous combustion, and self-heating.

At temperatures above 280 °C, these reactions cause the degradation of hemicellulose to produce gaseous CO, CO_2, phenols, acetic acid, and other highly volatile hydrocarbons. In addition, during torrefaction, the lost hydrophilic bonds made the product more hydrophobic, thereby improving its storage stability. The solid biomass contains about 30% of dry mass, resulting in more energy per unit of mass (i.e., 30% higher MJ/kg) based on torrefaction severity [35]. The solid product has similar utilization performance to coal used in power boilers and acts as a quality enhancer for a multi-fuel feedstock [47]. **Table 1** shows the comparison of some characteristics of woodchips, torrefied biomass, charcoal, and coal [48,49]. **Figure 3** shows a graphic representation of the fuel properties of raw biomass, torrefied biomass, and coal [50].

Table 1. Fuel properties of woodchips, torrefied biomass, charcoal and bituminous coal [32,48,49].

Properties wood	Wood	Torrefied biomass	Charcoal	Coal
Moisture content (%wt.)	30–45	3	1–5	10–15
Calorific value (MJ/kg)	9–12	19.90	30–32	23–28
Volatiles (% db)	70–75	-	10–12	15–30
Fixed carbon (% bd)	20–25	-	85–87	50–55
Bulk density (kg/L)	0.20–0.25	0.23	0–0.20	0.80–0.85
Vol. energy density (GJ/m^3)	2.00–3.00	4.70	7.60–6.40	18.40–23.80
Dust	Average	High	High	Limited
Hygroscopic properties	Hydrophilic	Hydrophobic	Hydrophobic	Hydrophobic
Biological degradation	Yes	No	No	No
Milling requirement	Special	-	Classic	Classic
Handling requirements	Special	-	Easy	Easy
Product consistency	Limited	-	High	High
Transport cost	High	-	Average	Low

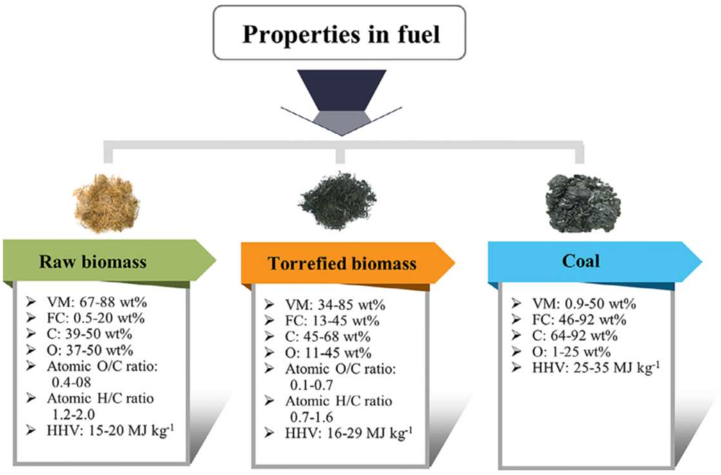


Figure 3. Fuel properties of raw biomass, torrefied biomass, and coal [50].

Torrefaction is suitable for the production of high-quality feedstock in pellets and briquettes, as well as a replacement for coal in thermal power plants and metalworking processes with significant energy and market potential [2,25,47,51]. Lange [52] viewed torrefaction as a more economical way of improving biomass properties. Despite the attractive potential of torrefaction and its extensive use in co-firing and energy applications, major limitations include difficulties in providing a passive environment, huge production costs of reactors, and design complexities [20]. Besides, Lal et al. [53] in Biomass and Research Development Board reported that the cost of collection, processing, storage, and transportation of torrefied products reportedly account for 25%–65% of total production costs. In addition, biomass feedstock costs highly varied based on collection techniques and local infrastructure; however, the biomass supply chain added an estimated 20%–40% to the cost of harvest and transportation, added an approximate 20%–65% to the total delivery cost, and added a 20%–25% increase to the pretreatment cost [54].

2.2. Classification and application of torrefaction

The main target of every torrefaction process is to enhance the quality of the torrefied product [54]. Torrefaction takes place under three conditions: dry, wet, and stream conditions (**Figure 4**). Dry torrefaction occurs in dry and non-oxidative (inert) or oxidative atmospheres at temperatures between 200 °C and 300 °C [55,56], while wet torrefaction occurs through water and dilute acid solution addition at temperatures of 180–260 °C [57,58]. Steam torrefaction improves biomass properties by utilizing high-temperature and high-pressure steam explosion reactors [59]. The torrefaction process aims at producing hydrophobic materials with improved grindability suitable for the production of durable and outdoor weather-resistant pellets or briquettes like coal. However, issues around the compatibility of torrefied biomass and torrefied dust material, achieving proven outdoor durable products, and leaching remained significant challenges.

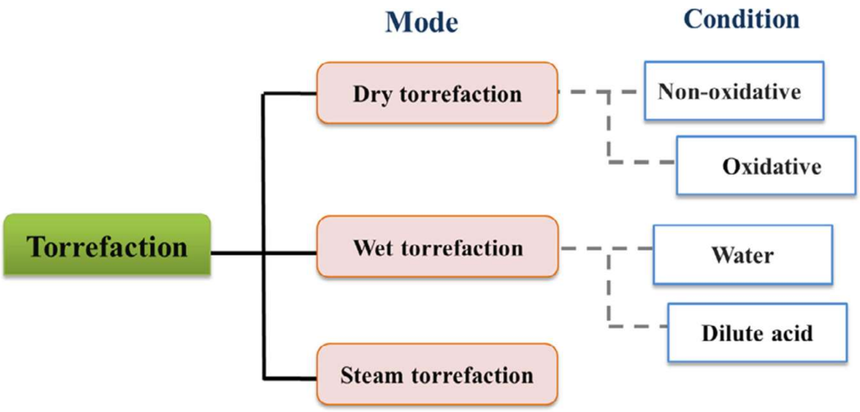


Figure 4. Classification of torrefaction [60].

The enhanced quality of torrefied biomass makes it an attractive process for combustion and gasification applications [60]. Torrefied product applications in co-firing processes with pulverized coal at electric power plants, as well as the production of value-added products replacing fossil fuels, have significantly promoted torrefaction applications in the energy supply chain. Other areas of product applications include utilization as a smokeless heat source for industrial, commercial, and domestic applications, for powering kilns and small-scale pellet burners, briquetting and as biochar for soil conditioning, and advanced bioenergy applications [61].

2.3. Torrefied product characteristics

Torrefaction enhanced biomass characteristics through the removal of oxygen and volatile contents from biomass, carbonization of hemicellulose, depolymerisation lignin and cellulose, and devolatilization of lignocellulosic biomasses [44]. Depending on the severity of the torrefaction process, the fibrous, tenacious, and hydrophilic properties of biomass tend to become brittle, grindable, and hydrophobic products. These behavioural changes have significant supply chain advantages, are cost-effective, and have properties compatible with coal [10]. Major quality characteristics of torrefied products include weight loss, high mass yield, energy yield, and density yield. These characteristics are influenced by some critical factors such as type of feedstock, temperature, dwell/residence time, rate of biomass heating, reaction temperatures, reactor environment, atmospheric pressure, feedstock flexibility, particle size, and moisture content [15,39,62]. Classified proximate and ultimate analysis data for torrefied products was published as part of the ISO 17225 Standard [10].

Weight loss: Material weight loss explains the proportion of volatile matter contents removed from the torrefied sample.

Mass yield (MY): This is the ratio of the final to initial mass of torrefied product and raw feedstock (*daf*), which is usually less than unity. Mass yield accounted for the quantity of solid products retained and

$$MY = \frac{M_{f,daf}}{M_{i,daf}} x100\% \tag{1}$$

Energy yield (EY): Energy yield explains the quantitative performance of the torrefaction process; this is the energy recovery after torrefaction, which is dependent on the moisture and ash contents of the biomass. The energy yield increased with a reduction in these elements [63]. Energy yield is temperature- and torrefaction-time-dependent and determines the effectiveness of torrefaction [39]. Volatile organic matter loss during torrefaction results in energy loss [64]. However, it increases the energy yield, which is usually greater than unity. Energy yield is expressed mathematically in terms of mass yield and energy density enhancement factor as follows:

$$EY = MYxEDEF\ (\%) \tag{2}$$

Energy balance (EB): The best mass and energy balance in torrefaction resulted when an estimated 30% of its initial dry mass and 10% of its initial energy content were lost in the process [65]. In this case, the energy yield is 100 less 10%, and the mass yield is 100% less 30% of the initial dry mass, as reported by Kim et al. [66]. Thus, the net process thermal efficiency is usually less than one, but it is dependent on both the heat and the chemical energy recovery.

Energy density: This is the amount of stored-up energy in a unit mass of material. Torrefied energy density is determined by comparing the raw biomass energy with the torrefied product. Phanphanich and Mani [67] reported low energy densities, typically 8–14 MJ/kg for raw biomass, while Medic et al. [68] reported a 19% increase in energy density due to mass loss in raw material at elevated temperatures.

Energy density enhancement (EDE): expressed mathematically as a percentage increase in torrefied energy density and raw feedstock:

$$EDE = \frac{HHV_{tp,daf} - HHV_{raw,daf}}{HHV_{raw,daf}} x\ 100\% \tag{3}$$

where $(HHV_{tp,daf})$ is the torrefied product HHV, $(HHV_{raw,daf})$ is raw biomass HHV.

Energy density enhancement factor (EDEF): Expressed as ratio of torrefied product in dry and ash free (*daf*) basis using the expression below.

$$EDEF = \frac{HHV_{tp,daf}}{HHV_{raw,daf}} \tag{4}$$

In addition, feedstock particle size influences the torrefaction process kinetics, reaction mechanisms, and residence time for a given heating rate [69,70].

2.4. A review of torrefaction reactor studies

Tumuluru et al. [39] gave a comprehensive review of different concepts and designs of torrefiers. Several reactors are presently available on the market, with over 100 patents and more than 50 technology developers [71]; however, the choice of design for commercial applications is dependent on feedstock type. Generically, the choice of reactor is characterized by the design, distinct modes of heat transfer, and gas-solid or solid-solid mixing patterns in the reactor [9].

Global efforts relating to process gas handling and contamination, process upscaling, predictability and consistency of product quality, densification of torrefied biomass, heat integration, and flexibility in using different input materials. Are accompanied by surmountable challenges such as reactor design and data regarding torrefaction costs at the pilot and commercial scales. Critical technical challenges facing technologies have necessitated global efforts towards the development of torrefaction technologies prior to commercialization [72]. The torrefaction design models based on thermodynamic equations could provide a solution to designing torrefaction systems for uniform control of product quality [10]. Further research efforts to optimize the torrefaction process to meet the end-use requirements for commercialization purposes are a work in progress [42,61,73–75].

Reactors are either directly heated or indirectly heated. The directly heated reactors have the biomass in direct contact with the heat source in the absence of oxygen; a typical example is a fluidized bed and batch reactor. The indirectly heated reactors have the heat source and the biomass in separate compartments in an inert environment within the reactor [71]. Junsatien et al. [28] and Nhuchhen [2] gave a comprehensive review of torrefaction reactors at three different scales and capacities, i.e., laboratory-scale reactors less than 20 kg/hr, pilot-scale reactors between 20 and 600 kg/hr, and commercial-scale reactors at more than 600 kg/hr. In addition, Tumuluru et al. [76] reported a positive biomass torrefaction result with a sand bed reactor, and Ghiasi [77] reported other authors’ works ranging from laboratory projects to pilot-scale projects. Ribeiro et al. [78] reported that some reactors operate at capacities of 8000–100,000 tons per year, mainly torrefying sawdust, while some facilities handle woody biomass [10]. Investigations revealed that the productivity of these reactors was constrained by the low heat intensity and mass transfer processes.

Several studies on a detailed review of selection criteria for biomass torrefaction reactors revealed factors influencing efficient torrefaction reactors in terms of heat transfer, cost, and complexity of operation [78]. Below are descriptions of different torrefaction reactors.

Fixed bed reactor: The fixed bed reactor (**Figure 5**) is a laboratory-scale torrefaction apparatus in which biomass is suspended in a metal mesh basket, dried, and torrefied in a furnace, then analyzed to understand the impact of process conditions on product properties [76,78,79]. The limitations of this reactor include poor heat transfer and temperature control [60].

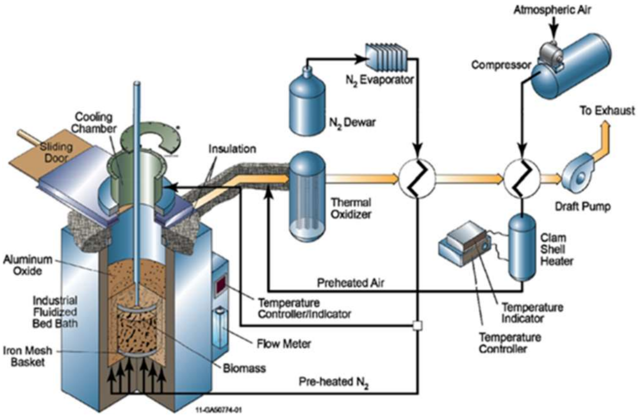


Figure 5. Fixed bed reactor for biomass torrefaction [76].

Rotary drum reactor: Rotary drum reactors (**Figure 6**) are electrically driven and require that the raw biomass be fed through the inlet as the drum rotates along a vertical axis while the torrefied product is discharged from the reactor outlet [79]. The biomass gyrates under gravity as the internal fixtures mixhe biomass heated indirectly via heaters installed from the outside of the drum, inside the drum, or by preheated inert or recycled torrefaction gas flowing through the drum, or via a combination of these modes of heating [44]. Manouchehrinejad and Mani [80] have developed other easy-to-scale-up simple technology models of rotary reactors. Disadvantages of this reactor include quick emissions and stoichiometry control along the sealed ends of the drum as it wears [39]. Other limitations include low thermal efficiency due to indirect heating, less plug flow, and scalability limitations compared to other reactors [60].

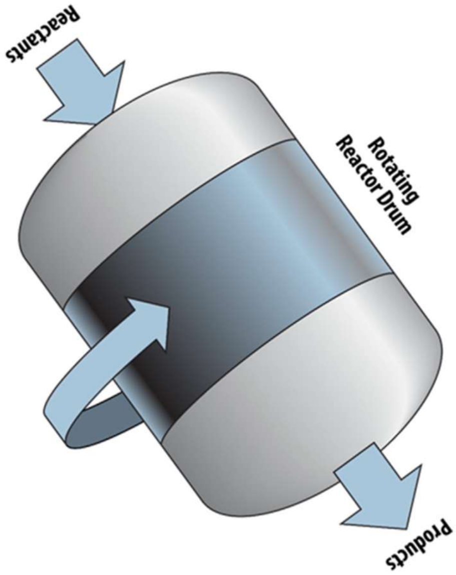


Figure 6. Rotary drum reactor for biomass torrefaction [60].

Microwave reactor: Microwave reactors (**Figure 7**) utilize electromagnetic radiation at frequency ranges of 300 MHz to 300 GHz [60] to rapidly, uniformly, and consistently heat biomass to agitate and set in motion the water molecules within the biomass, resulting in an increase in internal energy that helps to recycle the biomass [39]. The two main mechanisms involved in microwave torrefaction are dipolar polarization and ionic migration [60]. The residence time for biomass within a microwave reactor depends on biomass type, size, radiation absorption capacity, and reactor power [39,81]. Several researchers have studied microwave reactors [82–84]. Tumuluru et al. [85] reported a sufficient torrefying residence time of six minutes with a maximum 21 MJ/kg calorific value and approximately 53% wt. carbon content, as opposed to 15 min to achieve the same calorific value using the thermal torrefaction technique.

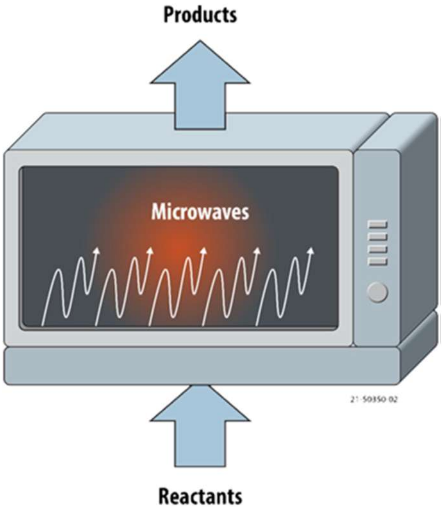


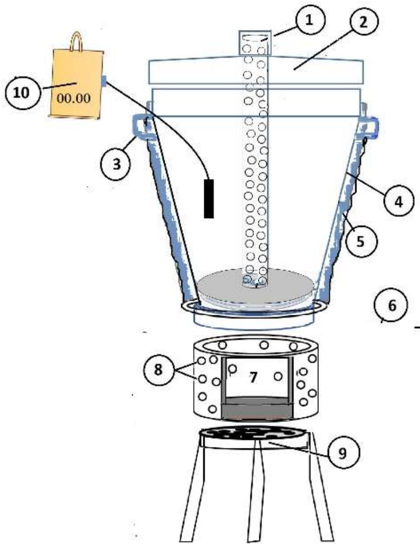
Figure 7. Microwave reactor for biomass torrefaction [60].

Fluidized bed reactor: In a fluidized bed reactor, biomass fluidization occurs using the inert hot gases blown from the bottom of the reactor. The raw biomass is size-reduced to smaller particles, requiring fluidization in the reactor to ensure a uniform temperature distribution throughout the bed [83]. The major challenge of this process is the size reduction of biomass to small sizes, which is very energy-intensive. The grinding energy is indirectly proportional to the grind size and inversely proportional to the moisture content. The smaller the grind size, the higher the grinding energy, and the higher the moisture content, the higher the grinding energy. The fluidization condition of a suitable inert gas velocity, which is usually higher than the minimum fluidization velocity, is essential. However, this system is not common for biomass torefaction applications.

Moving bed reactors: Two common designs of moving bed reactors are horizontal and vertical bed reactors. The horizontal moving bed reactor moves biomass with the aid of screw augers along a parallel axis into the torrefier. During this movement, the biomass is preheated by gas, or heating elements located within the reactor, in an opposing direction. This design is less efficient for heating biomass using preheated torrefier gas than the gas counter-flow design and has to rely more on indirect heating through the reactor walls. The potential benefit of this design is reduced tar and moisture buildup in the torrefier as compared to the counter-flow designs. Horizontal moving bed reactors are relatively cheaper and simpler to adapt to compared with large-scale industrial reactors. However, they are limited in production capacity due to uneven biomass heating, excessive product charring, and condensed tar and coke buildup, which tends to plug the system.

The vertical moving bed reactor operates in an opposing direction to the horizontal moving bed reactor with gravity downflow of biomass and buoyant heated gas upflow [44]. In other designs, there are internal stirrers to prevent particle bridging. An essential consideration in the cost of the torrefaction process is the blower cost [60]. The compact, simple design, optimized conditions, lower blower cost, and high heat transfer rate of the reactor give it an advantage over other reactors [60]. Sarkar et al. [86] provided more details about studies on switch grass biomass using vertical moving bed reactors and miscanthus and white oak sawdust using fixed bed torrefaction in collaborative work with Oklahoma State University [39].

Batch reactor: The laboratory batch reactor utilizes the concept of co-firing in the pulverized coal-fired stove [87] to develop a simple direct-heating torrefaction reactor for sawdust heating (**Figure 8**). During operation, the biomass poured into the reactor receives heat directly from the heating chamber through primary air vents at the base. The charcoal, when ignited at a full-gate opening, provided a maximum primary air supply to support ignition. However, the gate is adjustable to regulate the primary air supply as torrefaction progresses. The air inlet vents at the lid provided supplemental secondary air to support feedstock torefaction from the top. After torrefaction, the torrefied products were cool to atmospheric temperature and stored for briquetting.



S/NO	PART LIST	QTY
1.	FLUE VENT	1
2.	REACTOR COVER	1
3.	HANDLE	2
4.	REACTOR CHAMBER	1
5.	BIOMASS	1
6.	SCREEN	1
7.	HEATING CHAMBER	1
8.	AIR VENTS	1
9.	REACTOR BASE	1
10.	GATE	1

Figure 8. Direct heating batch reactor [12].

2.5. Review of torrefied products performance characteristics

Tumuluru et al. [49] carried out a broad-based review on the performance of torrefied products in energy generation with consideration to process reactions and carbonization, while Pahla et al. [88] investigated the changes in the properties of torrefied cow dung (animal waste), corncobs, and pinewood (Pinus radiata) against those of coal. They concluded that corncobs and pinewood responded better to torrefaction and co-fired with coal for energy production. In addition, cow dung utilization in biogas production through anaerobic digestion is common. Bridgeman et al. [31], in their study of reed canary grass and wheat straw torrefaction at 230, 250, 270, and 290 °C for 30-minute residence times, found that the moisture content decreased from an initial value of 4.7% to 0.8%. However, Adnan et al. [25] reported the torrefaction of empty fruit bunch (EFB) and palm kernel shell (PKS) materials at temperatures of 150 ℃.

Mamvura et al. [89] reported product characteristics comparable to coal at temperatures between 275 and 300 ℃, and residence times between 20 and 40 min, maintaining a heating rate of 10 ℃/min within the reactor temperatures. In another study, Bridgeman et al. [31] discovered temperature as the most significant parameter affecting energy crop grindability (willow and Miscanthus), which implied that biomass pulverization becomes easier as the torrefied biomass properties approach those of coal. Torrefaction improves the combustion characteristics of biomass by removing moisture and volatile matter from the raw materials, making the torrefied product typically brittle and easily grindable, with significant energy and market potential in comparison to the combustion reactivity of coal and wood. It equally has the potential to increase its heating value by approximately 17%, and its equilibrium moisture decreased by approximately 73% compared with its raw material [90].

Bridgeman et al. [31] found that mass and energy yields for woody biomass ranged from 61–82% and 73–92%, while for agro-biomass it was 25–76% and 29–81%, respectively. In a related review, Chen et al. [91] reported that below 290 ℃, biomass degraded into different components at different temperatures and rates. The experiment also concluded that torrefied products at higher temperatures have low moisture content in storage. Pelaez-Samaniego et al. [92] reported that varying the temperature from 200 to 350 ℃ during the torrefaction of Ponderosa pine could cause pyrolysis and established that the lignin decreased with an increase in temperature. Nhuchhen and Basu [70] investigated the torrefaction of poplar wood under mild pressure of 200–600 kPa in a batch reactor and concluded that the effect of replacing air with nitrogen was significant at higher temperatures. Hill et al. [93], during the torrefaction of Pinus *radiata* wood chips, found that increasing the temperature resulted in the production of hydrophilic crystal products. These studies showed the significance of temperature, material moisture, residence time, and material type on the final solid products.

2.6. Empirical study on torrefaction using a batch reactor

Feedstock collection: Gmelina arborea sawdust was produced from a table saw machine with a specialty teeth blade and a 4-inch, 1-TPI blade on a CD 4 band saw machine, respectively, from a local sawmill along Amagu-Okue road in Ishiagu [12]. The feedstock was sorted to remove foreign matter such as stone pebbles, leaves, visible bark, etc.

Reactor design considerations: In the design of the reactor, the following are some considerations kept in focus:

- Size of reactor: The reactor chamber is the frustum of a conical cylinder with a closed lower end perforated as an air vent for heated primary air to penetrate the biomass in the reactor.
- Size of combustion chamber: The combustion chamber is cylindrical with air vents and a gate for charcoal feed. The volume of the cylindrical chamber determines the size of the chamber.

- The air required for combustion: The airflow per unit mass of charcoal was computed using the formula,

$$AFR = \frac{\varepsilon x FCR x SA}{\rho_a} \tag{5}$$

where: AFR = airflow rate (m^3/hr), ε = equivalence ratio, (0.3–0.4), FCR = fuel consumption rate (kg/hr), *SA* = Theoretical air required to burn 1kg of charcoal (7.1:1 kg), ρ_a= air density (1.25 kg/m^3).

1) Apparent air velocity: This is the rate of airflow within the fuel, computed using the expression below,

$$V_s = \frac{AFR}{Area\ of\ inner\ combustion\ chamber} \tag{6}$$

where: V_s = apparent air velocity, (m/s), AFR = airflow rate, (m^3/hr).

2) Energy input: This is the fuel energy input into the reactor, computed using the formula,

$$Q_n = HV_f.FCR.\eta \tag{7}$$

where: Q_n = heat energy needed, MJ/hr, HV_f = heating value of fuel (charcoal) (28 MJ/kg), *FCR* = fuel consumption rate, ~0.19 kg/hr, η = stove efficiency, (80%).

3) Torrefaction experiment: Torrefaction process accomplished between 250–300 °C with limited air supply at three residence times of 30, 45, and 60 min [62,94]. The batch reactor chamber was filled with a weighed sample of Gmelina arborea sawdust. Charcoal was fed into the heating chamber and ignited, with air supply to the chamber controlled by a metal gate and air vents around the chamber. A K-type digital thermocouple with a temperature range of 50 °C to 1300 °C, manufactured by Digital Instrument, Italy, attached to the insulator monitors the temperature within the upper chamber as the sawdust roasts in limited air.

The reactor cover is taken off intermittently to release some of the volatile materials in the form of misty gases and trace quantities of coagulated organic compounds visible as condensed black crystals on the cover. At the expiration of the residence period, the remaining solid material with higher fixed carbon and fewer volatile matters was recovered from the reactor. After torrefaction, the char obtained was stored in bags for densification. The following reaction influenced the torrefaction process, according to Li [95].

$$Biomass \rightarrow \left\{ \begin{matrix} v_{co}CO + v_{co_2}co_2 + v_{CH_4}CH_4 + v_{H_2}H_2 \\ \text{Released gases} \end{matrix} \right\} + \left\{ \begin{matrix} Torrefied\ biomass \\ \text{solid residues} \end{matrix} \right\} \tag{8}$$

3. Results and discussion

3.1. Economic analysis of torrefaction

The bio-renewable market significantly thrives in biochemical and thermochemical conversion applications, including torrefaction, gasification, and pyrolysis. The economic analysis of the torrefaction process centers around an assessment of the economic feasibility of the production and utilization of torrefied biomass and, consequently, the market perspectives, keeping in mind the value additions compared with other studies. The key focus is the return on investment (RoI) and the torrefaction value addition when compared to raw products. Commercially developed markets and pricing structures for torrefied biofuels are not readily available, with assumptions of premium payment for potentially superior storage products similar to coal [10].

Several economic assessment models are available to evaluate the cost of biomass torefaction [96]. The assessment model includes an analysis of the costs of biomass, electricity, labor, investment, and transportation in comparison with the cost of coal replacement [10]. These analyses reported torrefaction production cost savings of over 3% above pelletization, with considerable transport and end-user savings [10]. There are reported cases of earlier torrefaction along the supply chain to preserve fuel quality while reducing transportation and storage costs [54]. Shah et al. [22] reported an estimated total torrefaction cost of $17.5/ton for a material with an initial moisture content of 30% wb and a processing temperature of 240 °C. Further reduction of this cost under optimal process integration and operating conditions is possible.

3.2. Performance characteristics of batch reactors

3.2.1. Physical and proximate characteristics of raw and torrefied sawdust

The physical and chemical characteristics of products produced in a batch reactor were evaluated to determine their performance characteristics. The particle lengths of raw sawdust used were 8.57 mm, with a mean standard deviation of 4.594 at a 95% confidence interval [97], and a mean density of 159 ± 0.02 kg/m^3 at a moisture content of 9.41%. The sample proximate analysis reported high volatile matter content (72.93%), low ash (2.19%), and carbon contents (17.10%) at 7.78% moisture content. The heating value of sawdust was 17.38 MJ/kg. The samples of untreated and torrefied sample products at different torrefaction times are shown in **Figure 9**.

Figure 9. Samples of untreated and torrefied sawdust produced at 30, 45, and 60 min [12].

The most significant physical characteristics observed in the torrefied samples were their colour and weight changes. The colour changed from light brown to golden brown with specks of black at 30 min (mild torrefaction) to dark brown at 45 min and dark colour at 60 min (severe torrefaction). Bello et al. [12] reported that beyond 60 min, the colour turned charred. Qualities of torrefied sawdust were in. The fixed carbon and ash contents increased with an increase in torrefaction time. The fixed carbon increased from 17.10% for untreated sawdust to 21.30%, 38.57%, and 65.38% at 30 min, 45 min, and 60 min torrefaction times, respectively. These increases were similar for ash contents, which also increased from 2.19% to 5.76%, 5.76%, and 5.76%, respectively, for torrefied sawdust. Mohamed et al. [98] obtained comparable results.

Torrefaction time has consequential effects on the product as volatile matter and fixed carbon contents are significantly changed. For instance, an increase in torrefaction time from 30 to 45 min increases the fixed carbon from 17.63% to 21.02% and reduces the volatile matter from 65.19% to 47.92%, implying a substantial amount of volatile and oxygenated compounds expelled from the hemicellulosic fractions through thermochemical reactions. Consequently, as the torrefaction time increases, the volatile matter further decreases while the fixed carbon simultaneously increases. These findings agreed with those of other studies, like Li [95], Adegoke et al. [99], and Mohamed et al. [98], in torrefying sawdust within the same range of temperatures and a 20 min residence period. The untreated HHV increased from 17.23 kJ/kg to 26.28 kJ/kg at 60 min of torrefaction time. These observed results agreed well with the findings of the studies by Ghani et al. [100] and Mohamed et al. [98].

3.2.2. Batch reactor performance

The performance of the batch reactor evaluated by percentage energy yield (EY), percentage loss in mass, and torrefaction degree showed that percentage energy yields at 30, 45, and 60 min were 36.33%, 58.10%, and 69.80%, respectively. The percentage weight loss and energy densification ratio increased as torrefaction time increased. The reactor's total energy input was 4.26 MJ/hr. The torrefaction degree varied from 10.61% ± 0.2%, 34.29% ± 0.2%, and 71.18% ± 0.2% for 30, 45, and 60 min respectively. The performance characteristics of the batch reactor were satisfactorily compared with literature results.

The solid mass yield of the products at 30 min, 45 min and 60 min residence times were 76.7%, 33.6%, 45 min and 28.2%, respectively. Expectedly, the solid mass decreased appreciably with an increase in torrefaction time. Similar studies by Lasode et al. [101] and Nhuchhen [2] found that torrefied woody biomass yielded 80 weight percent after 30 min, whereas non-wood torrefied biomass yielded 50 weight percent at 240 and 300 °C, respectively. The energy yield, which describes the energy contents of material (determined by mathematical expression), retained after torrefaction increased from 36.33 wt.%, 58.10 wt.%, and 69.89 wt.% with an increase in torrefaction time of 30 min, 45 min and 60 min respectively. The energy yield at 30 min was below the limits of literature values of 55–93 wt% for energy woods [102,103]. This implies that the energy yield of sawdust is not significantly affected by the 30 min torrefaction time, as evident in the values of Energy Density Enhancement (EDE).

Furthermore, the Energy Densification Ratio (EDR) at 30, 45, and 60 min (0.91, 1.08, and 1.35) and Energy Density Enhancement Factor (EDEF) at 1.01, 1.21, and 1.51, respectively, increased due to an increase in torrefaction time and consequently increased the energy yield. Weight loss was associated with volatile matter decomposition as well as moisture. These observations were similar to those obtained by Nhuchhen [2] in the thermal pretreatment of cylindrical-shaped poplar wood and loblolly pine samples, respectively.

3.3. Torrefaction cost analysis

The cost analysis of reactor acquisition and the cost per ton of torrefying sawdust at different residence times, as presented in **Table 2,** show that the total unit cost of acquiring the reactor was NGN 92, 800.00 ($12.00). Compared with the cost of commercial reactors ($50–100.00), the batch reactor is cheaper. Sawdust is available in dumpsites and regarded as waste meant for disposal, so the cost per ton is at giveaway prices. The cost of charcoal is relatively high at 8000.00/50 kg bag due to the competitive nature of charcoal in the face of the rising cost of fossil fuel. Labour costs are cheap at 2700.00 per ton. Feedstock transportation per ton is high at 12,000.00 due to the rising cost of fossil fuels (diesel).

Table 2. Operational cost torrefaction operation.

Operations	Amount (NGN)	Product quality
Cost of reactor	92,800.00	-
Cost of biomass/ton	5000.00	-
Cost of charcoal/50 kg bag	8000.00	-
Feedstock transportation cost	12,000.00	-
Torrefaction at 30 min/ton	15,000.00	Low
Torrefaction at 45 min/ton	20,300.00	High
Torrefaction at 60 min/ton	25,500.00	High
Torrefaction labour cost/ton	2700.00	-

Torrefaction cost per ton varied with time, increasing with an increase in residence time. The cost variation between 45 and 60 min is high compared with the characteristic properties of products obtained under each process. The cost of torrefaction significantly increased torrefying for 60 min without significant improvement in quality compared to 45 min torrefaction. This implies that there are more cost-benefits to recycling at 45 min than at 60 min.

4. Conclusion

Economic analysis of bio-renewable materials from the perspective of production and processing revolves around the economic feasibility of sustainable production and utilization of biomass and market prospects, keeping return on investment (RoI) and value additions in focus. The technoeconomic benefits of batch reactor technology, product characteristics, and economic analysis showed that batch torrefaction significantly improved the physical quality and combustion performance of torrefied products. The products have better grindability and storability compared to raw biomass. The costs of torrefied sawdust products exhibit comparable characteristics with agricultural biomass, with assurance that its positive characteristics translate to an economic advantage over the high cost of torrefier reactors. A critical technical challenge in the development of torrefaction processes relates to the possibility of product quality uniformity. Proving optimal reactor design considerations and simplicity of process conditions for the production of stable and high-quality products is a work in progress. Comparing with other thermal pretreatment methods, torrefaction was considered a more economical way of improving biomass properties.

Conflict of interest: The authors declare no conflict of interest.

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