



Design of a Torrefaction Process for Application in Botswana. A Review

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Abstract

The design of torrefaction processes for biomass conversion are examined in this research, with a focus on the potential of this process as a sustainable energy source in Botswana. Torrefaction is a thermal treatment process that improves properties of raw biomass for use as a biofuel or for co-feeding with coal to reduce carbon emissions. The potential of biomass as an alternative energy source is has not been fully realized in Botswana as there are research gaps on the available biomass resource and its suitability for treatment processes such as torrefaction. This review identifies the gaps and gives information on reactor design, process conditions, and economic feasibility specific to torrefaction. This gives a foundation for the research to be done specific to Botswana for implementation of a torrefaction plant. The review shows ways in which the government of Botswana is promoting the development of the clean energy sector.

Keywords: Torrefaction, Biomass, Biofuels, Reactor Design, Renewable Energy, Botswana, Biomass Conversion

1. Introduction

Biomass is any organic materials that can be used as renewable energy sources such as wood, agricultural residues and other plant materials. It plays a big role in the global transition to sustainable energy, because the world faces the challenges of climate change due to use of fossil fuels [1]. Nations have formed organizations such as the Organization for Economic Cooperation and Development (OECD) committed to ceasing the use of coal before 2030 [2]. Biomass provides a viable alternative for reducing carbon emissions and enhancing energy security, because of its potential for conversion into biofuels.

Globally, coal had a share of 36% in total electricity generation in 2023 [3], showing the dependence on coal worldwide. In Botswana coal is primarily used for electricity generation by the Botswana Power Cooperation (BPC). However, BPC falls short on its supply and Botswana imports some of its power from neighboring South African utility, Eskom, which also uses coal fired power stations [4]. Because of this alternative renewable energy resources that can replace coal are being explored. Despite the availability of biomass resources, characteristics like low bulk density and low energy density present a major limitation to their application in energy production [5]. To improve biomass properties pretreatment processes such as torrefaction can be used to convert raw biomass into biofuels.

Torrefaction has emerged as a promising technology for improving the energy density and storage properties of biomass [6]. However, despite the availability of different biomass types in Botswana as documented by Sekhela and Kgathi [7], research on the application of torrefaction within the country is still lacking. Botswana has many bush encroachment and invasive woody biomass species but there is a gap in understanding the quantity and suitability of the biomass for use in biofuel production. Many global studies on torrefaction have focused on common feedstocks as summarized by Mamvura and Danha

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[8] while Botswana's local biomass resources have not been extensively studied. Research has demonstrated that torrefaction conditions such as temperature and heating rate can vary based on the biomass feedstock [9], yet little is known about how these parameters should be adjusted to optimize the process for local feedstocks. This knowledge gap restricts the efficient use of the local biomass resource as a suitable feedstock for biofuel production. The purpose of this review is to evaluate torrefaction technologies and their applicability in Botswana with consideration of sections such as reactor selection, drying, condensation and economic feasibility. Detailed explanations on various aspects affecting the sections to be discussed will be given. This comprehensive review will serve as a starting point for future research and development in the area of utilization of biomass for biofuel production in Botswana.

2. Overview of the torrefaction process

Torrefaction is a thermal treatment method operated at 200-300 °C in an inert or oxygen –limited environment to enhance biomass qualities for use as fuel or feedstock [10]. This process leads to partial decomposition of biomass, releasing volatile compounds and transforming its chemical structure. It improves biomass properties and converts it into a biofuel with reduced atomic oxygen to carbon (O/C) and hydrogen to carbon (H/C) ratios, moisture content, yielding a high energy density and improved grindability [11]. The overall torrefaction process occurs in five stages; heating, pre-drying (where free water is evaporated at about 100 °C), intermediate heating at 200°C in which physically bound water is released, torrefaction and solids cooling where the torrefied product is cooled to room temperature [6]. The primary role of torrefaction in biomass upgrading is to increase the energy density of the material by reducing its oxygen content and increasing the carbon content of biomass [12]. According to Aria et al, torrefaction improves the grindability and calorific value of the biomass.

The modes of torrefaction include dry, wet and steam torrefaction [13]. Dry torrefaction utilizes carrier gases such as nitrogen, flue gas or air. It can either be oxidative or non-oxidative depending on the carrier gas used. Oxidative torrefaction has a higher reaction rate as compared to non-oxidative because the presence of oxygen accelerates the exothermic reactions that occur during decomposition reducing the overall torrefaction time [14]. Due to a lack of moisture, dry torrefaction requires precise temperature control to prevent combustion. Wet torrefaction utilizes pressurized water. It is more suited for biomass with a high moisture content. Steam torrefaction uses steam as a medium under high temperature and pressure to torrefy biomass [15]. It is typically carried out at temperatures between 200-260 °C [10]. The heating rate in steam torrefaction are usually higher because the high heat capacity of steam allows for transfer of more heat to the biomass [16]. Both wet and steam torrefaction offer advantages in terms of enhanced biomass degradation and greater yield of solid carbon-rich products. [17].

The degradation of biomass is affected by torrefaction conditions but the biomass composition also plays a crucial role. Biomass is made up of cellulose, lignin, hemicellulose, and ash [18]. Hemicellulose degrades the most while cellulose and lignin degrade to a lesser extent during torrefaction, [19]. The relative proportions of these constituents depend on the nature of biomass. For example, hemicelluloses contents (wt%) in hardwood, softwood, and agricultural biomass are 15-36 wt%, 11-27 wt%, and 22-35 wt%, respectively; cellulose contents in these materials are 39-54 wt%, 41-50 wt%, and 24-50 wt%, respectively, and lignin contents are 17-29 wt%, 27-30 wt%, and 7-29 wt%, respectively [9].

3. Reactor Selection and Design

The most important component in a torrefaction system is the torrefaction reactor as the efficiency of the torrefaction process mainly depends on it. Several types of reactors have been used for torrefaction including fixed bed, microwave, moving bed

and fluidized bed reactors. Fixed bed reactors are commonly used for small-scale and laboratory research due to their simple design and precise control over residence time and temperature. However, they struggle with uneven heat distribution and are less efficient for large-scale operations.

Fluidized-bed reactors are highly efficient in terms of heat transfer, making them ideal for rapid processing of biomass. Here the biomass is fluidized using inert hot gases blown from the bottom of the reactor. They are scalable and suitable for industrial applications but require fine biomass particles and careful control of gas flow, which adds complexity to their operation. Microwave reactors use microwave radiation as a heat source and this aids in heating biomass more rapidly and continuously [17]. Moving bed reactors use mechanical systems to transfer biomass between the reactor entrance and exit [20]. Biomass is passed through a series of temperature-controlled chambers and each chamber exposes the biomass to higher temperatures [17]. Table 1 presents the advantages and disadvantages of the reactors.

Hidayat et al [21], used a modified version of a fixed bed reactor i.e., a fixed counterflow multi-baffle reactor to torrefy bamboo pellets. This modified version came about due to the uneven distribution of heat in a fixed bed reactor. The concept of vortex flow is applied to achieve uniform heat distribution across the production area. This advantage is significant, as it reduces the risk of product non-uniformity caused by uneven heating. The reactor enhances heat efficiency and distribution and increases product yield. Torrefaction using a Fixed COMB reactor reduced moisture content by 99.8%.

Table 1: A summary comparing different reactor types [10] [13] [22] [23].

Reactor type	Advantages	Disadvantages
Fixed bed	<ul style="list-style-type: none"> • Low initial capital cost • Simple design 	<ul style="list-style-type: none"> • Irregular heat distribution.
Fluidized bed	<ul style="list-style-type: none"> • Good heat conducting properties. • Easily scalable • Good temperature control 	<ul style="list-style-type: none"> • High initial costs due to additional gas requirements • Limited to smaller particle sizes.
Moving bed	<ul style="list-style-type: none"> • High heat transfer rate • Easily scalable 	<ul style="list-style-type: none"> • Susceptible to fouling • Difficult to control temperature • Pressure drop can be a problem in the reactor.
Microwave	<ul style="list-style-type: none"> • Good temperature control • High heat transfer rate 	<ul style="list-style-type: none"> • High operating cost because of the need of an integrated heater

4. Process Integration and Economic Feasibility

Various plant designs have been explored in literature, however their application in Botswana strongly depend on many factors including but not limited to the amount of biomass available and scale of operation, which is linked to the economic feasibility. Some of the plant designs and their specific material flows are discussed below.

A steam torrefaction pilot plant using Eucalyptus globulus biomass with a reactor that adopted a multi-hearth furnace concept with three sections. The plant flow was a steam generator to produce the steam, a steam super heater and superheated steam was sent to the torrefaction reactor. A feedstock flowrate of 68-70 kg/hr was used [24]. The volatiles produced during torrefaction exit together with the steam and were utilized for fresh steam heating then condensed and collected. The application of such a plant in Botswana, could be costly for a large scale operation because of Botswana's less developed

infrastructure. However, systems where the heat emitted by the torrefaction gases is used to sustain the process, reduce dependence on external energy sources and lower the operational costs.

The torrefaction plant designs by Bergman et al [25], using pilot scale plants made use of different reactors, the indirectly heated screw reactor, directly heated rotary drum and directly heated moving bed reactor. The main focus of this study was design of the plant. And it highlighted that in design, some of the aspects to look at are feedstock flexibility, autothermal operation, heating mode on reactor technology and the operating parameters. Plants that allow for flexibility in feedstocks could be advantageous for Botswana's diverse biomass resources.

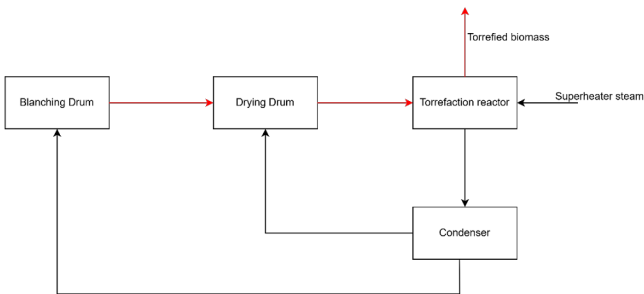


Fig. 1. A typical representation of a steam torrefaction plant. Biomass and steam flow in a countercurrent manner. Steam comes at its highest temperature into the reactor, then mixed with vapors from the torrefaction process and directed to the condenser to separate the steam from other vapors. The steam is used at the pre-drying stage. Biomass is transported according to the red arrows.

Botswana is working towards encouraging the application of sustainable energy, this is shown by the inclusion of sustainable environment in vision 2036 under pillar 3, energy security [26]. In 2024, the Ministry of Minerals and Energy confirmed its collaboration with National Agricultural Research and Development Institute (NARDI) and the University of Botswana on a project called the Biodiesel Production Project. This shows that the government is actively working towards promoting clean energy in various sectors [27]. Additionally the government collaborated with the United Nations Development Programme (UNDP) to provide guidelines on biofuel as a tool to guide potential local and foreign investors [28].

5. Mechanical and Chemical Design Considerations

Torrefaction process efficiency, scalability, environmental effect, and economic viability are all significantly influenced by design [13]. Mechanical design is mainly concerned with designing the actual components of the system while chemical design is concerned with selecting and integrating the process steps to create a functioning system [29]. In mechanical design aspects such as types of material for each unit to be used based on the function of the unit. In a torrefaction reactor because temperatures would be between 200-300°C a high-temperature material would be required. Other aspects to consider are the dimensions of the unit, rotational mechanism if there is to be any, mechanisms to control biomass residence time [30], heat insulation and distribution are considered.

In terms of chemical design, aspects such as types of heat source and the interaction with the biomass, energy balance calculations are critical to achieve biofuel properties required. In the same vein effects of biomass particle size, moisture content and heat transfer rate, thermal decomposition rates and integration of gas recycling systems are essential to improve efficiency [25].

5.1 Design of equipment

The design of these reactors is based on the kinetics of the reaction (a sufficient residence time must be provided for the reaction to proceed), safety factors, mass transfer, and heat transfer [31]. Sinnott [32], outlines a general procedure for reactor design. In these steps, choosing reactor conditions, such as conversion are important because this helps in determination of the size of the reactor.

Drying is an essential biomass pretreatment operation prior to torrefaction. Drying improves the overall process efficiency as less time is spent on removing moisture from biomass in other downstream sections [9]. It is used to decrease the amount of moisture in the biomass to improve efficiency of thermochemical conversion processes [33]. The types of dryers include rotary drum, flash, fluidized bed and fixed bed dryers. Dryer selection is mainly based on physical properties of material to be dried, quality indicators, drying kinetics, and amount of moisture in the feed and product [34]. According to Mujumdar [34], design of dryers is based on the preferred characteristics of the product, the estimated drying times and rate of heat transfer.

Condensers are also found in various torrefaction plants. These are used to condense materials in the system that are to be used in other sections of the system. Condensers are designed based on the composition of the vapor being condensed, whether single component or multicomponent (a mixture) [31]. In the thermal design of a condenser the most important parameter is the overall heat transfer coefficient between the vapor and coolant [31]. To design multicomponent condenser, estimations of heat transfer coefficients are made by empirical (approximate methods) and analytical methods [32].

6. Conclusion

Torrefaction is an excellent method for transforming raw biomass into a biofuel with improved properties such as moisture content and energy density. Given that Botswana is dependent on coal to generate electricity torrefaction presents great potential to provide Botswana with a clean energy source from the available biomass resources. However, it is evident that more research on Botswana's biomass species is required to determine the suitability for conversion into biofuel by torrefaction and to access the economic feasibility of implementing such a process in Botswana.

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