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Enhancing Energy Content of Biofuel Production from Biomass: A Review

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Abstract

The paper presents a review on how to improve the energy content of solid biofuel recovery from biomass. This addresses the urgent requirement for sustainable and renewable energy options. The objective of this paper is to address the inherent difficulties related to the use of biomass, such as its high moisture content and low energy density, by utilizing the torrefaction process. This study provides significant insights into biomass conversion technology by analyzing the features of biomass feedstock, creating an optimized technique and design, and assessing the combustion and energy characteristics of the torrefied products using proximate and ultimate analyses. This improves the effectiveness, financial viability, and ecological sustainability of energy derived from biomass, aiding Nigeria's shift to renewable energy and contributing to global initiatives to combat climate change and foster sustainable development. This study underscores the significance of ongoing innovations and process improvements in order to fully utilize the advantages of biomass torrefaction in the shift towards renewable energy sources.

Keywords

Biomass, energy content, optimization, torrefaction, solid biofuel

1. Introduction

It is crucial to tackle the inherent difficulties related to biomass utilization in order to fully harness its potential as a renewable energy source. Raw biomass is hindered by its elevated moisture content, low bulk density, and inadequate grindability, which make transportation, storage, and combustion processes more challenging. Torrefaction is a thermal pre-treatment method that efficiently alters biomass by breaking down hemicellulose and partially breaking down cellulose and lignin, resulting in increased energy density, reduced water absorption, and improved capacity to be ground. This conversion greatly enhances the biomass's appropriateness for diverse energy uses, including as co-firing with coal in power plants, pellet manufacture, and biochar utilization. It is crucial to develop a fixed bed torrefaction reactor that can optimize these enhancements in order to overcome the obstacles to optimal biomass utilization [1].

Biomass is plentiful and varied, providing a sustainable substitute for fossil fuels. Nevertheless, the efficient use of it is impeded by inherent characteristics such as elevated moisture content, reduced bulk density, and inadequate grindability. The characteristics of biomass, like as its qualities, can make transportation, storage, and combustion procedures more complex, which in turn decreases the overall efficiency of biomass energy systems. Torrefaction is a process where biomass is heated at moderate temperatures (200-300°C) in an environment without oxygen [2]. This causes the breakdown of hemicellulose and partial degradation of cellulose and lignin in the biomass. The end result is a product that has increased energy density, resistance to water, and ease of grinding. This conversion greatly enhances the biomass's appropriateness for many energies uses, such as blending with coal in power plants, producing pellets, and utilizing biochar.

Optimizing fixed-bed torrefaction reactors is essential for improving energy efficiency and economic feasibility, hence making torrefied biomass a viable and competitive substitute for traditional fuels. Fixed bed reactors are known for their simple design and easy operation, which makes them suitable for processing various types of biomass feedstock. Nevertheless, achieving uniform heat dispersion and efficient thermal breakdown throughout the biomass bed continues to be a difficult task. Novel reactor configurations, integrating cutting-edge heat transfer materials and Optimized reactor structures, are required to enhance process efficiency, diminish energy usage, and decrease operational expenses [3]. This study seeks to overcome design obstacles in order to create a reactor that can greatly improve the economic and operational viability of torrefaction processes. The goal is to make high-quality torrefied biomass more appealing for energy markets.

Torrefied biomass is a renewable energy source that can be used to achieve sustainable development goals and mitigate climate change. This is important from an environmental standpoint. Torrefied biomass provides significant environmental advantages compared to fossil fuels, such as decreased greenhouse gas emissions, reduced pollutant release during combustion, and increased possibility for carbon sequestration through the application of biochar. The objective of this research is to enhance environmental sustainability through the creation of a fixed bed torrefaction reactor that can effectively convert different types of biomass feedstock into superior solid biofuel. Moreover, the use of agricultural leftovers, forestry by-products, and other waste biomass materials for torrefaction promotes the valorization of waste and the concepts of a circular economy [3]. The review contributes to the advancement of scientific and technological understanding as well as offering empirical data and techno-economic analyses to assist policymakers and industry stakeholders in formulating supportive policies and promoting market development for torrefied biomass.

The need for sustainable and renewable energy sources has grown in importance in the twenty-first century due to the combined effects of depleting fossil fuel supplies and growing environmental awareness. The dependence on fossil fuels such as coal, oil, and natural gas has resulted in substantial environmental deterioration, including the release of pollutants into the air, the production of greenhouse gases, and the phenomenon of global warming. These concerns have prompted a worldwide endeavor to discover alternative energy sources, among which are biofuels that are both sustainable and ecologically sound. Biofuel is a notable and adaptable resource among the different renewable energy options, with the potential to make a big impact on the global energy matrix [4].

One of the primary sources of biofuel is the biomass. Therefore, biomass is the term used to describe organic matter that comes from living or recently lived animals, such as plant and animal remains. This extensive category includes a diverse range of items, including agricultural waste (such as crop residues and animal manure), forestry residues (such wood chips and sawdust), industrial trash (such as food processing waste), and even municipal solid garbage. The use of biomass for energy generation provides numerous environmental and socio-economic advantages. It is classified as carbon-neutral because the carbon dioxide (CO2) emitted during the burning or decay of biomass is about equivalent to the CO2 taken in by the plants during their development. This equilibrium aids in reducing the effects of greenhouse gas emissions, which is a crucial element in the fight against climate change. Biomass can be converted into useful energy through different processes, which can be broadly categorized into biochemical, thermochemical, and physical ways. Each of these conversion processes possesses distinct benefits and is appropriate for various kinds of biomass feedstock and end-use applications [4]

Torrefaction, which can also be described a moderate pyrolysis process, is a highly promising technology for improving the energy content and characteristics of solid biofuels. Torrefaction is the process of subjecting biomass to temperatures ranging from 200°C to 300°C in an atmosphere with little or no oxygen. Torrefaction is a procedure that eliminates moisture and volatile organic compounds from biomass, resulting in a dry, fragile, and high-energy product called torrefied biomass or bio-coal. Torrefaction enhances the energy density of biomass, improves its grindability, reduces its hygroscopic character, and enhances its burning qualities. As a result, it becomes a compelling substitute for conventional solid fuels like coal [5].

Integrating torrefied biomass into the energy supply chain has numerous benefits. Initially, the heightened energy density of torrefied biomass diminishes expenses related to transportation and storage, rendering it financially feasible for extensive uses. Furthermore, the enhanced combustion characteristics of torrefied biomass make it appropriate for blending with coal in current power plants, enabling a gradual shift from non-renewable fossil fuels to sustainable energy sources without the need for substantial alterations to existing infrastructure. Furthermore, the manufacturing of torrefied biomass can create an additional source of income for agricultural and forestry sectors, thereby encouraging the implementation of sustainable land management techniques and fostering rural development [5]-[6].

Ultimately, the advancement and refinement of biomass torrefaction methods, specifically utilizing fixed bed reactors, are crucial in the progression of renewable energy technology. Torrefaction is a process that improves the energy content and fuel characteristics of biomass, making it easier to use organic materials for energy production. The adoption of bio-based energy sources facilitates international endeavors to combat climate change, diminish greenhouse gas emissions, and foster sustainable development. Given the ongoing changes in the global energy sector, the significance of renewable energy sources like biomass cannot be emphasized enough. Ongoing research and innovation in this field are crucial to fully harness the potential of biomass as a fundamental element of the renewable energy portfolio [7]-[8].

2. Biomass Conversion Process

Biomass conversion procedures are necessary for converting raw biomass into energy forms that may be utilized, such as solids, liquids, or gases. The processes can be classified into three main categories: biochemical, thermochemical, and physical. Every conversion process has distinct benefits, restrictions, and uses that are specifically designed for various biomass feedstock and desired energy outputs [9].

A. Biochemical Conversion

Biochemical Conversion (BCC) refers to the process of converting biomass into biofuels or other valuable chemicals using biological organisms or enzymes (Baker and Elliott, 1988; Ugwu et al., 2022). Biochemical conversion employs biological mechanisms to decompose organic matter and transform it into fuels that are abundant in energy. This method is especially appropriate for biomass varieties that include a high amount of carbohydrates, such as plant matter and animal byproducts [10]. The two main BCC processes are anaerobic digestion and fermentation, which are discussed as follows:

Anaerobic Digestion involves breaking down organic materials in the absence of oxygen, resulting in the production of biogas and nutrient-rich digestate. Anaerobic digestion is a process where microorganisms break down organic waste without the presence of oxygen, resulting in the production of biogas. Biogas is mostly made up of methane (CH4) and carbon dioxide (CO2). This process happens through a series of stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Various types of microorganisms aid each stage of the process, converting complex organic chemicals into simpler ones, which finally results in the production of biogas. Biogas can be utilized for purposes such as heating, generating electricity, or serving as a fuel for vehicles once it has undergone purification. The residual digestate, which contains a high concentration of nutrients, can be utilized as either a soil conditioner or a fertilizer [10].

Fermentation on the other hand is the process of transforming sugars found in biomass into ethanol through the action of yeast or bacteria. This procedure is extensively employed in the manufacturing of bioethanol from crops such as corn, sugarcane, and wheat. The fermentation process generally involves pretreatment, which aims to break down complex carbohydrates into fermentable sugars, enzymatic hydrolysis to convert polysaccharides into monosaccharides, fermentation to convert sugars into ethanol, and distillation to purify the ethanol. Bioethanol can serve as a sustainable alternative fuel for internal combustion engines, either in its pure form or when mixed with petrol. This helps to reduce dependence on petroleum-based fuels and mitigate the release of greenhouse gases.

B. Thermochemical Conversion

Thermochemical conversion (TCC) refers to the process of converting energy from one form to another through the use of heat and chemical reactions. TCC techniques entail the utilization of heat to break down biomass into various forms of energy carriers. These procedures are adaptable and capable of handling a diverse variety of biomass feedstock, including those with a substantial amount of lignin that are not easily processed by biochemical methods [11]-[12]. TCC processes of significance encompass combustion, pyrolysis, gasification, and torrefaction, which are explained as follows:

Combustion: This refers to the process of biomass burning in the presence of oxygen, resulting in the production of heat. The thermal energy can be utilized for room heating, industrial operations, or the production of electricity by means of steam turbines. Combustion is a widely used technology with a lengthy track record, although it faces problems in terms of emissions management and efficiency enhancements [13]-[14].

Pyrolysis: It is a process that entails subjecting biomass to high temperatures without the presence of oxygen, causing it to break down into charcoal, bio-oil, and syngas. The distribution of these products is contingent upon the temperature and rate of heating. Biochar, a carbonaceous substance, has the potential to serve as both a soil amendment and a solid fuel. Bio-oil, an intricate blend of organic molecules, can be enhanced to produce liquid fuels or chemicals. Syngas, a blend of hydrogen, carbon monoxide, and other gases, has versatile applications such as generating heat and power, or serving as a raw material for the production of synthetic fuels [15].

Gasification: This method involves partially oxidizing biomass at high temperatures. This process produces syngas, which has several applications such as generating electricity, synthesizing chemicals, or serving as a fuel for internal combustion engines. Gasification provides superior efficiency and cleaner combustion in comparison to direct burning. Efforts are underway to enhance efficiency and minimize the production of tar through the development of advanced gasification technologies, including fluidized bed and plasma gasifiers [16].

Torrefaction: Torrefaction is a thermal decomposition process that involves heating biomass to temperatures ranging from 200 to 300°C in an atmosphere with little or no oxygen. Torrefaction is a procedure that eliminates moisture and volatile components from biomass, resulting in a dry, fragile, and high-energy product called torrefied biomass or bio-coal. Torrefaction improves the energy density, grindability, and hydrophobicity of biomass, hence facilitating its storage, transportation, and co-firing with coal in power plants [17].

C. Physical Conversion

Physical conversion (PC) methods entail the utilization of mechanical means to alter the physical characteristics of biomass, hence improving its suitability for energy-related purposes. These methods do not undergo chemical changes to the biomass, but rather enhance its energy density, handling, and storage properties. One of the top PC methods is called pelletization, this method involves the compression of biomass into compact pellets. This procedure entails pulverizing the biomass into a fine powder, dehydrating it to decrease the moisture level, and subjecting it to intense pressure for compression. The resultant pellets possess a consistent size and shape, a high energy density, and a low moisture content, rendering them well-suited for household heating, industrial boilers, and co-combustion with coal [18].

Briquetting is a process that methods of PC that involves compressing biomass into larger, solid shapes known as briquettes, which are similar to pellets. Briquettes are commonly employed in poor nations for the purpose of heating and cooking. They serve as a cleaner and more effective substitute for conventional biomass fuels such as wood and charcoal [18].

Densification is also another PC methods that involves the process of compacting loose biomass resources into compact forms, like as bales or logs, in order to decrease their volume and enhance the efficiency of transportation and storage. This procedure is particularly advantageous for agricultural residues and forestry by-products, which are frequently voluminous and challenging to manage. Every one of these conversion steps has a vital function in the total utilization of biomass for the production of energy. The selection of conversion technique is contingent upon various aspects, including the nature of the biomass feedstock, the required energy output, economic issues, and the environmental consequences. By utilizing a variety of conversion methods, it is feasible to harness the extensive potential of biomass as a renewable energy source, so contributing to a more sustainable and resilient energy future [19].

3. Overview of Torrefaction

Torrefaction has attracted significant interest among thermochemical processes because of its ability to improve the energy content and characteristics of solid biofuels. Torrefaction is a thermal decomposition process that requires heating biomass to temperatures ranging from 200°C to 300°C in an atmosphere with little or no oxygen. Torrefaction is a procedure that removes moisture and volatile organic compounds from biomass, transforming it into a dry, brittle, and energy-dense material called torrefied biomass or bio-coal. There are numerous benefits of torrefaction. Firstly, it greatly enhances the energy density of biomass, hence improving its transportability and storability. Furthermore, torrefied biomass exhibits a superior calorific value in comparison to raw biomass, so rendering it a more proficient source of fuel. Furthermore, the method diminishes the ability of biomass to absorb moisture, hence improving its ability to be stored for longer periods without the risk of microbial deterioration. Torrefied biomass demonstrates enhanced grindability, making it beneficial for applications that necessitate finely ground biomass particles [20].

The studies [21] has been instrumental in advancing our understanding of the effects of torrefaction on various biomass feedstock. It completed extensive research on the process of torrefaction applied to wood and agricultural leftovers. Their study showcased that torrefaction greatly improves the energy density, grindability, and hydrophobicity of biomass, thereby making it a feasible substitute for coal in power production. The discoveries are similar to [22] work which also indicated the improvement in the overall properties of terrified biomass. Through a rigorous analysis of the alterations in the physical and chemical properties of torrefied biomass, it has been determined that this procedure not only enhances the qualities of the fuel, but also enables its seamless incorporation into pre-existing coal-fired power plants without significant adjustments. The researches had established a strong scientific foundation for the advancement of torrefaction technologies, highlighting the potential of torrefied biomass as a viable and effective source of sustainable energy.

A. Application of Fixed Bed Reactors in Biomass Torrefaction.

Fixed bed reactors are commonly selected for biomass torrefaction because of its straightforward design, convenient operation, and capacity to process different types of biomasses feedstock. In a stationary bed reactor, biomass is placed in a permanent bed, and heat is applied to facilitate the torrefaction process. The fixed bed configuration offers even heating and stable product quality, making it a desirable choice for industrial applications [23].

Therefore, an effective fixed bed torrefaction reactor requires careful attention to reactor design, heat transfer methods, process parameters, and biomass feedstock properties. The design of the reactor must guarantee a consistent distribution of temperature and efficient transfer of heat in order to optimize the quality of the torrefied product. Optimal torrefaction characteristics can be achieved by optimizing process parameters such as temperature, residence duration, and heating rate, while simultaneously minimizing energy usage. Furthermore, the torrefaction process and its results are greatly affected by the physical and chemical characteristics of the biomass feedstock, including its moisture content, particle size, and composition [24]. The development of a stationary biomass torrefaction reactor for producing and increasing the energy content of solid biofuel is a crucial advancement in renewable energy technologies. Torrefaction enhances the energy density and fuel characteristics of biomass, enabling the effective utilization of organic substances for energy generation. This approach includes reactor design, process optimization, feedstock characterization, and economic analysis. Torrefaction technology's progress offers potential for fostering a sustainable energy future, diminishing our dependence on fossil fuels, and tackling the environmental issues of the 21st century [25].

B. Chemical Analysis of Torrefaction

Torrefaction is a process that utilizes temperatures between 200 oC and 300 oC without the presence of oxygen. The process results in the removal of low molecular weight volatile chemicals and gases from the biomass, as a result of the dehydration and decarboxylation processes of the long polysaccharide chains. Figure 1 depicts the several phases encompassed in the torrefaction process as reported by [25]. According to his study, he outlined the five main stages of torrefaction as follows: initial heating, pre-drying, post-drying, intermediate heating, torrefaction, and solid cooling as shown in Figure 1. The process is begun by subjecting the biomass to heat until it reaches a temperature at which evaporation occurs. Subsequently, the temperature is raised to a level exceeding 100°C, which facilitates the gradual extraction of moisture from the biomass at a consistent pace throughout the initial drying stage. In the third phase, the objective is to eliminate any moisture present in the biomass, however it is anticipated that there would be some reduction in mass due to the loss of moisture as well as the evaporation of volatile organic compounds such as extractives and oils. Torrefaction of biomass occurs when the temperature exceeds 200°C.

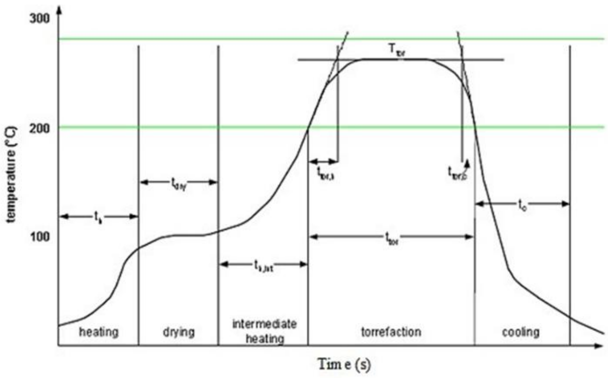

Figure 1: Different Stages of Torrefaction [25]

To determine the precise duration of torrefaction, the reaction time is employed instead of the residence time of the reactor. Reaction time refers to the combined duration required to raise the temperature of the biomass from 200°C to the desired ultimate temperature (torrefaction), as well as the duration that the biomass remains at the desired temperature [26].

4. Torrefaction Reactors

Several torrefaction reactor designs, including fixed bed, microwave, rotary drum, fluidized bed, and auger-driven, have been conceived, experimented with, or utilized. [27] categorize torrefaction reactors according to the biomass movement and the techniques of heat transfer. The authors mention several types of reactors that commercial firms are currently developing, including the fixed bed reactor, rotary drum reactor, screw reactor, microwave reactor, moving bed reactor etc. The selection of a reactor is significantly influenced by the type of biomass feedstock. Resources that are valuable for scientific investigation are less valuable for business purposes. Every reactor design possesses its own set of benefits and drawbacks. The primary objective of torrefaction reactor design research has been to achieve a consistently torrefied product. This is accomplished by creating a reactor that ensures consistent heat and mass transfer.

5. Gaps In Previous Studies

There is a lack of thorough evaluations of the environmental and economic impacts of torrefaction technology. Additional investigation is required to assess the environmental consequences and economic efficiency of various torrefaction methods and reactor configurations, taking into account elements such as energy usage, emissions, and overall sustainability. It is imperative to conduct long-term research to assess the sustained performance of torrefied biomass in different applications, especially its co-firing capabilities with coal in power plants. Research should prioritize investigating the enduring stability, handling, and storage characteristics of torrefied biomass to guarantee its effective incorporation into current energy infrastructures [27].
The advancement of reactor designs that integrate automation and real-time monitoring has the potential to improve the efficiency and uniformity of the torrefaction process. Advancements in reactor technology that enable enhanced regulation of process parameters and more efficient heat transfer methods are essential for the progress of the area. Achieving effective energy content and commercialization of biomass torrefaction technology, it is crucial to address these deficiencies by conducting focused research and review. This will ultimately contribute to the locally transition to renewable energy sources.

6. Determination of A Typical Reactor Parameters

A typical torrefaction reactor consists of a segment, the base reactor and the cover cone as showed in Figures

2 and 3. The base reactor taking the shape of a cylinder while its volume (V_b) is calculated from equation 1.

$$V_{base} = \pi r^2 h \quad (1)$$

The volume of its cover cone is determined as contained in equation 2.

$$V_{c-cone} = \frac{h_c}{3} \pi {r_c}^2 \quad (2)$$

The total volume of the reactor is stated in equation 3.

$$V_t = V_b + V_c \quad (3)$$

Where: h, h_c r and r_c are the heights and radii of the cylinder (mm), respectively.

The average pressure developed inside the reactor vessel within a temperature difference of 28 °C to 300 °C is determined as contained in equation 4.

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2} \quad (4)$$

Where: P_1, P_2, v_1, v_2, T_1 and T_2 are initial and final pressure in Kpa, l volume m^3 and temperature in k

The thickness of pressure vessel is estimated using equation 5

$$t = \frac{Pd}{2 \cos \alpha (SE - 0.6p)} \quad (5)$$

Where: s, t, r, d, p, E and α are maximum allowable stress value (kpa), thickness (mm), inside radius (m), inside diameter (m), maximum allowable working pressure (kpa), joint efficiency and half the angle of the apex of the cone, respectively.

The power required per unit time to raise the reactor temperature to 300 °C is stated in equation 6.

$$P = \frac{mC\Delta\theta}{t)} \quad (6)$$

Where: m, C and Δθ are mass (kg), specific heat capacity (J/kgk) and change in temperature (k), respectively.

A. Theoretical Analysis of Operating Conditions

The theoretical analysis involves evaluating the effects of temperature, residence time, and gas flow rate on biomass properties. The operating conditions are optimized through a series of experiments, where parameters such as mass loss, energy yield, and by-product composition are continuously monitored and analyzed. Fixed bed reactor, stainless steel with excellent temperature resistance, heating system with a temperature control device capable of reaching temperatures up to 400°C, temperature sensors, gas flow control system etc are some of equipment needed in the process [27].

B. Raw Materials

Biomass feedstock refers to the organic matter that is used as a raw material for the production of biofuels or other forms of energy, such as wood chips, agricultural leftovers, or other lignocellulosic material. Inert gases, sealing materials, insulation materials, calibration gases, stainless steel fittings and connectors, tubing and piping with high temperature resistance, and glassware and containers of laboratory grade quality. These lists of equipment and materials guarantees the availability of all essential equipment and supplies required for the efficient development and functioning of the fixed bed biomass torrefaction reactor. The primary objective is to optimize the energy density of solid biofuel while ensuring the experimental equipment is both safe and accurate [28].

C. Fabrication a Typical Reactor Components

The fabrication process should involve manufacturing the reactor components according to detailed engineering drawings. Assembly should include integrating the heating elements, temperature sensors, gas flow controls, and condensation units into the reactor. Ensuring all components meet the required specifications and safety standards is critical as showed in Figures 2 and 3.

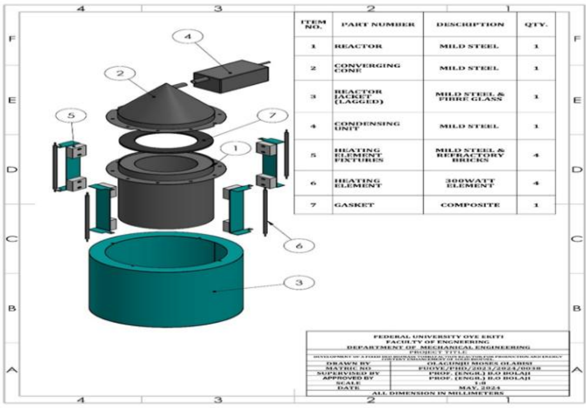

Figure 2: A typical exploded view of torrefaction reactor

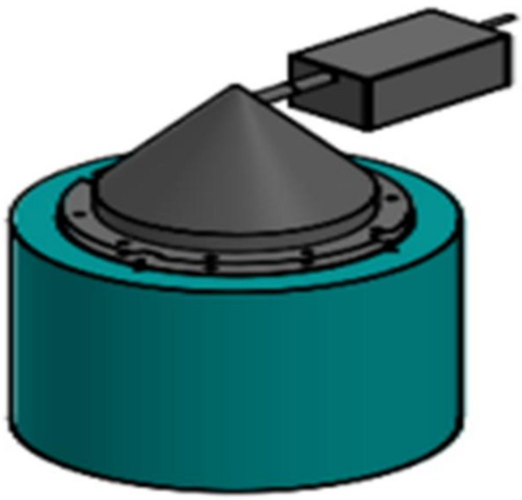

Figure 3: A typical Torrefaction Reactor

D. Experimentation and Test Run

The experimental phase involves preparing the biomass feedstock, setting up the experimental apparatus, and conducting the torrefaction process under various conditions. The Instruments is calibrated, and data such as temperature profiles, mass loss, and gas compositions are recorded for analysis.

E. Experimental Setup and Feedstock Preparation

The research methodology includes selecting suitable biomass feedstock, such as wood chips and agricultural residues, based on their availability and desired properties. The biomass is then processed using choppers, grinders, and sieve shakers to achieve a uniform particle size distribution. Subsequently, all measurement instruments, including thermocouples, data loggers, and gas analyzers, are installed and calibrated for accurate data collection during the experiments.

F. Torrefaction Process Optimization

This involves identifying key process parameters such as temperature, residence time, and inert gas flow rate. A series of experiments is conducted, varying these parameters to study their effects on biomass properties and energy content. Throughout the experiments, temperature profiles, mass loss, gas composition, and by-product yields are continuously monitored and recorded.

7. ANALYTICAL METHODS

Standard proximate and ultimate analyses to determine the moisture, volatile matter, fixed carbon, ash content, and elemental composition (C, H, N, S, O) of raw and torrefied biomass must be carried out. The higher heating value (HHV) of the biomass samples using calorimetric analysis to assess energy content enhancement would be performed. Analyze the composition of gases evolved during torrefaction using gas chromatography to understand the decomposition process and by-product formation is essential.

A. Data Analysis and Interpretation

This involves assessing the uniformity and stability of the reactor's temperature distribution through detailed temperature profile analysis. Furthermore, mass and energy balances is calculated to determine mass loss and energy yield from the torrefaction process, thereby evaluating its efficiency. Comparative analysis is conducted to compare the properties of raw and torrefied biomass, allowing for the determination of improvements in fuel quality. Some of the data analyses cover the following areas:

a. Temperature Profile Analysis

Temperature profile analysis is monitored and analyzed over the temperature distribution within the reactor during torrefaction. Data from thermocouples placed at various positions in the reactor is logged continuously. Temperature profiles is plotted over time to assess the uniformity and stability of the heating process, providing insights through graphs of temperature versus time and identifying any temperature gradients or inconsistencies.

b. Mass loss Estimation

Mass loss calculation is another critical aspect, aimed at determining the extent of biomass decomposition and mass reduction during torrefaction. Initial and final weights of the biomass samples would be measured, and the percentage mass loss is calculated and correlated with torrefaction conditions. The yields percentage mass loss data is tabulated and plotted against torrefaction temperatures and durations to obtain the relationship between the variables.

c. Proximate and Ultimate Analysis

Proximate and ultimate analyses is conducted to analyze the changes in the chemical composition of the biomass before and after torrefaction. Proximate analyses of moisture, volatile matter, fixed carbon, ash; and ultimate analyses of carbon, hydrogen, nitrogen, sulfur, oxygen are performed on both feedstock and torrefied biomass to ascertain quality and percentage elemental compositions.

d. Energy Content Analysis

Energy content determination is essential for quantifying the enhancement in energy content due to torrefaction. Calorimetric analysis is used to measure the higher heating value (HHV) of the raw and torrefied biomass. Data obtained were compared, the untreated with treated biomass, demonstrating the energy content improvements resulting from the torrefaction process.

e. Gas Analysis

Gas analysis characterizes the gases evolved during torrefaction and assess their composition. Gas samples collected and analyzed using gas chromatography (GC) concentrated on major gases (CO, CO2, CH4, H2). The resulting gas composition data would indicate the relative proportions of different gases, providing insights into the gaseous by-products of torrefaction.

f. Tar and Moisture Analysis

Tar and moisture collection analysis quantifies and characterizes the by-products of the torrefaction process. Tar and moisture collected in the cold traps is weighed and analyzed for chemical composition using appropriate techniques. The data on tar yield and moisture content, with chemical characterization results summarized the efficiency and by-product formation during torrefaction.

g. Performance Evaluation of the Reactor

Performance evaluation combines data from temperature profiles, mass loss, chemical analyses, and energy content to assess reactor efficiency and process optimization. This comprehensive performance includes efficiency metrics, operational stability assessments, and recommendations for improvements, providing a holistic view of the reactor's performance.

h. Statistical Analysis

Statistical analysis ensures the reliability and significance of the experimental results. Statistical tools such as ANOVA, regression analysis, and hypothesis testing are applied to the collected data. The statistical summaries and significance levels presentation would validate the findings and support the conclusions drawn from the study, ensuring the robustness of the data analysis process. This comprehensive data analysis plan enables a thorough assessment of the fixed bed biomass torrefaction reactor's performance, providing insights into the process's efficiency and the quality of the resulting solid biofuel. The results form the basis for optimizing reactor design and operational parameters, ultimately contributing to the development of a more effective biomass torrefaction technology.

i. Optimization and Validation

The process optimization utilizes collected data to refine torrefaction parameters, aiming to maximize energy content and improve process efficiency. Following optimization, repeated experiments are conducted under these optimized conditions to validate the reactor's performance and ensure the reproducibility of the results.

B. Power Consumption and Cost Determination

The power consumption is determined using equation 7.

$$P=VI \qquad (7)$$

The cost of power consumption is calculated using equation 8.

$$C_{(t)}=PCt \qquad (8)$$

Where P is the power in watts, V is the voltage in volts, and I is the current in amperes, $C_{(t)}$ is the cost, t is the time in hours and C is the cost per kilowatt-hour.

8. CONCLUSION

The review advances renewable energy science, technology, and practice. Full knowledge of the torrefaction process, especially in fixed-bed reactor systems, is a major contribution. This study shows how biomass feedstocks thermally decompose and reveals the chemical and physical changes that occur during the process by researching biomass torrefaction kinetics. This fundamental information helps optimize torrefaction settings for maximum biomass quality. The economic feasibility, energy efficiency, and environmental implications to influence governmental, market, and industry investments were assessed. Torrefied biomass enhanced the viable alternative to fossil fuels with quality high energy content, aiding the shift to renewable energy and climate change mitigation. The following conclusions were drawn from the review for energy content improvement.

I. Types and techniques of biomass conversions were extensively discussed for better biomass conversion approaches.

II. An overview of torrefaction technology and applications of fixed bed reactors in biomass torrefaction were stated to improve biofuel production.

III. Procedural analysis of both unterrified and torrefied products for comparison as viable substitutes to fossil fuels with high quality is substantiated.

IV. Detailed pictorial determinations of typical reactor parameters were enumerated.
V. Torrefaction process optimization towards energy content enhancement is possible.
VI. The importance of data analysis and interpretation for economic values was made easy.
VII. Proximate and ultimate analyses of biomass and torrefied energy content to shift to renewable energy to combat environmental pollution are encouraged.

References

1) Mamvura, T. A., Pahla, G., and Muzenda, E. (2018). Torrefaction of waste biomass for application in energy production in South Africa. South African Journal of Chemical Engineering, 25, 1–12. https://doi.org/10.1016/j.sajce.2017.11.003
2) Tumuluru, J. (2016). Effect of Deep Drying and Torrefaction Temperature on Proximate, Ultimate Composition, and Heating Value of 2-mm Lodgepole Pine (Pinus contorta) Grind. Bioengineering, 3(2), 16. https://doi.org/10.3390/bioengineering3020016
3) Urishev, B. (2019). Decentralized Energy Systems, Based on Renewable Energy Sources. Applied Solar Energy, 55(3), 207–212. https://doi.org/10.3103/S0003701X19030101
4) Van der Stelt, M. J. C., Gerhauser, H., Kiel, J. H. A., and Ptasinski, K. J. (2011). Biomass upgrading by torrefaction for the production of biofuels: A review. Biomass and Bioenergy, 35(9), 3748–3762. https://doi.org/10.1016/J.BIOMBIOE.2011.06.023
5) Jaya, S. T., Sokhansanj, S., Hess, J. R., Wright, C. T., and Boardman, R. D. (2011). A review on biomass torrefaction process and product properties for energy applications. Industrial Biotechnology, 7(5), 384–401. https://doi.org/10.1089/ind.2011.7.384
6) Tumuluru, J., Boardman, R., Wright, C., and Hess, J. (2012). Some Chemical Compositional Changes in Miscanthus and White Oak Sawdust Samples during Torrefaction. Energies, 5(10), 3928–3947. https://doi.org/10.3390/en5103928
7) Basu, P., Rao, S., and Dhungana, A. (2013). An investigation into the effect of biomass particle size on its torrefaction. The Canadian Journal of Chemical Engineering, 91(3), 466–474. https://doi.org/10.1002/cjce.21710
8) Lasode, O. A., Balogun, A. O., and McDonald, A. G. (2014). Torrefaction of some Nigerian lignocellulosic resources and decomposition kinetics. Journal of Analytical and Applied Pyrolysis, 109, 47–55. https://doi.org/10.1016/j.jaap.2014.07.014
9) Nakyai, T., Authayanun, S., Patcharavorachot, Y., Arpornwichanop, A., Assabumrungrat, S., and Saebea, D. (2017). Exergoeconomics of hydrogen production from biomass air-steam gasification with methane co-feeding. Energy Conversion and Management, 140, 228–239. https://doi.org/10.1016/j.enconman.2017.03.002
10) Soltani, S., Mahmoudi, S. M. S., Yari, M., and Rosen, M. A. (2013). Thermodynamic analyses of an externally fired gas turbine combined cycle integrated with a biomass gasification plant. Energy Conversion and Management, 70, 107–115. https://doi.org/10.1016/J.ENCONMAN.2013.03.002
11) Gil, M. V., Casal, D., Pevida, C., Pis, J. J., and Rubiera, F. (2010). Thermal behaviour and kinetics of coal/biomass blends during co-combustion. Bioresource Technology, 101(14), 5601–5608. https://doi.org/10.1016/j.biortech.2010.02.008
12) Khaliq, A., and Kaushik, S. C. (2004). Thermodynamic performance evaluation of combustion gas turbine cogeneration system with reheat. Applied Thermal Engineering, 24(13), 1785–1795. https://doi.org/10.1016/J.applthermaleng.2003.12.013
13) Beena, P. (2012). Biomass characterization and its use as solid fuel for combustion. Iranica Journal of Energy and Environment, 8, 34-43. https://doi.org/10.5829/idosi.ijee.2012.03.02.0071
14) Williams, A., Jones, J. M., Ma, L., and Pourkashanian, M. (2012). Pollutants from the combustion of solid biomass fuels. Progress in Energy and Combustion Science, 38(2), 113–

137. https://doi.org/10.1016/J.PECS.2011.10.001

15) Stefanidis, S. D., Kalogiannis, K. G., Iliopoulou, E. F., Michailof, C. M., Pilavachi, P. A., and Lappas, A. A. (2014). A study of lignocellulosic biomass pyrolysis via the pyrolysis of cellulose, hemicellulose and lignin. Journal of Analytical and Applied Pyrolysis, 105, 143–150. https://doi.org/10.1016/J.JAAP.2013.10.013
16) Zanzi, R., Sjöström, K., and Björnbom, E. (2002). Rapid pyrolysis of agricultural residues at high temperature. Biomass and Bioenergy, 23(5), 357–366. https://doi.org/10.1016/S0961-9534(02)00061-2
17) Prins, M. J., Ptasinski, K. J., and Janssen, F. J. J. G. (2006). Torrefaction of wood: Part 1. Weight loss kinetics. Journal of Analytical and Applied Pyrolysis, 77(1), 28–34. https://doi.org/10.1016/J.JAAP.2006.01.002
18) John, N., Fathima, P. S., Harsha, V. S., Paul, N. M., and Nisha, P. (2023). Physical conversion of biomass: dewatering, drying, size reduction, densification, and separation. In Handbook of Biomass (pp. 1–28). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-6772-6_37-1
19) Abdoli, M. A., Golzary, A., Hosseini, A., and Sadeghi, P. (2018). Wood pellet as a renewable source of energy. Springer International Publishing, 12, 44-52. https://doi.org/10.1007/978-3-319-74482-7
20) Zhang, X., Xu, M., Sun, R., and Sun, L. (2006). Study on Biomass Pyrolysis Kinetics. Journal of Engineering for Gas Turbines and Power, 128(3), 493–496. https://doi.org/10.1115/1.2135816
21) Bridgeman, T. G., Jones, J. M., Shield, I., and Williams, P. T. (2008). Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. Fuel, 87(6), 844–856. https://doi.org/10.1016/j.fuel.2007.05.041
22) Jaya, S. T., Ghiasi, B., Soelberg, N. R., and Sokhansanj, S. (2021). Biomass torrefaction process, product properties, reactor types, and moving bed reactor design concepts. Frontiers in Energy Research, 9, 41-49. https://doi.org/10.3389/fenrg.2021.728140
23) Zohuri, B. (2021). New approach to energy conversion technology. molten salt reactors and integrated molten salt reactors. Energies, 21, 85–136. https://doi.org/10.1016/B978-0-323-90638-8.00003
24) Shankar, J., Sokhansanj, S., T., C., and Kremer, T. (2012). Analysis of volatiles and other products from biomass torrefaction process. In advanced gas chromatography - progress in agricultural, biomedical and industrial applications. Technology, 14, 56-60. https://doi.org/10.5772/33488
25) Ugwu, C. O., Ozor, P. A., Ozoegwu, C. G., Ndukwe, A., and Mbohwa, C. (2022). Biomass Resources in Nigeria and the Conversion Pathways. Proceedings of the International Conference on Industrial Engineering and Operations Management, 14, 1–11. https://doi.org/10.46254/AF03.20220142
26) Tumuluru, J. S. (2015). Comparison of Chemical Composition and Energy Property of Torrefied Switchgrass and Corn Stover. Frontiers in Energy Research, 3, 54-59. https://doi.org/10.3389/fenrg.2015.00046
27) Chen, W.-H., Lin, B.-J., Lin, Y.-Y., Chu, Y.-S., Ubando, A. T., Show, P. L., Ong, H. C., Chang, J.-S., Ho, S.-H., Culaba, A. B., Pétrissans, A., and Pétrissans, M. (2021). Progress in biomass torrefaction: Principles, applications and challenges. Progress in Energy and Combustion Science, 82, 100-107. https://doi.org/10.1016/j.pecs.2020.100887
28) Phanphanich, M., and Mani, S. (2011). Impact of torrefaction on the grindability and fuel characteristics of forest biomass. Bioresource Technology, 102(2), 1246–1253. https://doi.org/10.1016/J.BIORTECH.2010.08.028