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Pyrolysis-Driven Biomass Energy Conversion: Reactor Design, Construction and Power Output Assessment

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Abstract: Biomass is emerging as a significant renewable energy resource in Bangladesh, contributing to the country's goal of increasing electricity generation from sustainable sources. This study focuses on the design, construction, and performance evaluation of a laboratory-scale slow pyrolysis reactor for biomass-to-electricity conversion. The reactor operates at temperatures between 400–600 °C under oxygen-limited conditions, producing biochar, bio-oil, syngas, and usable thermal energy. An optimized reactor configuration was developed to enhance heat transfer efficiency and overall system performance. The generated thermal energy was successfully converted into electrical energy through a steam-driven turbine-generator system. Experimental results demonstrated that reactor temperature plays a critical role in determining both product distribution and power output. At the optimized temperature of 500 °C, the system achieved a balanced yield of biochar (≈32 wt.%), bio-oil (≈38 wt.%), and syngas (≈30 wt.%), ensuring efficient energy recovery. The maximum stable electrical power output was recorded at 15 W, with voltage around 12 V (DC) and current approximately 1.25 A, corresponding to an electrical efficiency of about 12.4% under optimal conditions. At lower temperatures (450 °C), power output decreased to 8 W due to insufficient syngas production, whereas at higher temperatures (550 °C), output slightly increased to 17 W but introduced thermal stress on the reactor system. The system also demonstrated stable frequency (50 Hz), acceptable power factor (≈0.92), and suitability for low-power applications such as LED lighting, mobile charging, and small electronic devices. Overall, the findings confirm that slow pyrolysis-based biomass conversion can be a viable decentralized renewable energy solution.

Keywords: Slow pyrolysis, biomass-to-energy, reactor design, biochar, syngas, renewable electricity, energy optimization.

Introduction

The global energy crisis and escalating environmental concerns have intensified the search for sustainable and carbon-neutral energy sources (Akhtar and Amin, 2011). Biomass, as a renewable energy resource, offers a viable alternative to fossil fuels due to its abundance, carbon neutrality, and potential for waste valorization (McKendry, 2002). Among various biomass conversion technologies, pyrolysis—a thermochemical decomposition process occurring in the absence of oxygen—has gained significant attention due to its ability to produce bio-oil, syngas, and biochar, which can be utilized for power generation, chemical production, and carbon sequestration (Bridgwater, 2012).

Pyrolysis-driven biomass conversion is particularly attractive because of its flexibility in feedstock selection, including agricultural residues, forestry waste, and energy crops (Mohan et al., 2006). The process can be tailored to maximize liquid (fast pyrolysis), gaseous (gasification), or solid (slow pyrolysis) products depending on reactor configuration, temperature, heating rate, and residence time (Huber et al., 2006). However, the efficiency and scalability of pyrolysis systems are heavily influenced by reactor design, which directly affects heat transfer, product yield, and energy output (Butler et al., 2011).

Several reactor types, such as fluidized bed, fixed bed, auger, and rotary kiln reactors, have been explored for biomass pyrolysis, each with distinct advantages and limitations (Bridgwater, 2003). Fluidized bed reactors, for instance, offer excellent heat transfer and high bio-oil yields, but their operational complexity and high costs pose challenges for large-scale deployment (Venderbosch and Prins, 2010). Conversely, fixed bed reactors are simpler but suffer from poor heat distribution and lower efficiency (Demirbas, 2004). Recent advancements in reactor design, including microwave-assisted and plasma pyrolysis systems, have shown promise in improving energy efficiency and product quality (Huang et al., 2016; Zhang et al., 2020).

Assessing the power output of pyrolysis systems is critical for their integration into renewable energy grids. The energy content of pyrolysis products (bio-oil: ~15–25 MJ/kg, syngas: ~10–20 MJ/Nm^3, biochar: ~25–30 MJ/kg) determines their suitability for combined heat and power (CHP) applications (Garcia-Nunez et al., 2017). However, challenges such as feedstock variability, reactor inefficiencies, and downstream processing requirements can significantly affect net energy output (Brown et al., 2011). Life cycle assessments (LCAs) and techno-economic analyses (TEAs) are essential to evaluate the sustainability and economic viability of pyrolysis-based power generation (Cherubini and Ulgiati, 2010).

This study focuses on optimizing pyrolysis reactor design and construction to enhance energy conversion efficiency and power output. By evaluating different reactor configurations, operational parameters, and product utilization pathways, we aim to provide insights into scalable and economically feasible biomass-to-energy systems. The findings will contribute to advancing sustainable energy technologies and supporting global decarbonization efforts.

Materials and Methods

Biomass is a versatile renewable energy source that can be converted into electricity through multiple pathways, including combustion, pyrolysis, gasification, liquefaction, and anaerobic digestion or fermentation, depending on its type and availability (Demirbas, 2007; McKendry, 2002). Among these, thermo-chemical processes are particularly valuable, as they transform biomass into higher-value or more convenient energy carriers and chemical products (Bridgwater, 2012). Pyrolysis, a widely studied thermo-chemical technique, involves thermal decomposition of organic material at 400–600 °C in the absence of oxygen (Venderbosch & Prins, 2010). This process converts complex biomass polymers into bio-oil, syngas, and biochar, which can serve as alternatives to conventional fossil fuels (Zhang et al., 2020). Product distribution and yield depend on feedstock composition and operating parameters, including temperature, heating rate, and residence time (Bridgwater, 2012). Woody biomass, such as wood chips, sawdust, and pellets, is particularly suitable for pyrolysis and combustion due to its high thermal energy content (McKendry, 2002). In this study, slow pyrolysis was applied to efficiently convert biomass into energy-dense products, optimizing energy recovery and product quality. The process workflow (Figure 1) outlines key stages, including pre-treatment, thermal decomposition, and product collection, enabling systematic analysis of feedstock properties and process parameters on energy yield and chemical composition. Subsequent sections describe the experimental setup, operational procedures, and analytical techniques employed to establish a robust framework for biomass-to-electricity conversion via pyrolysis.

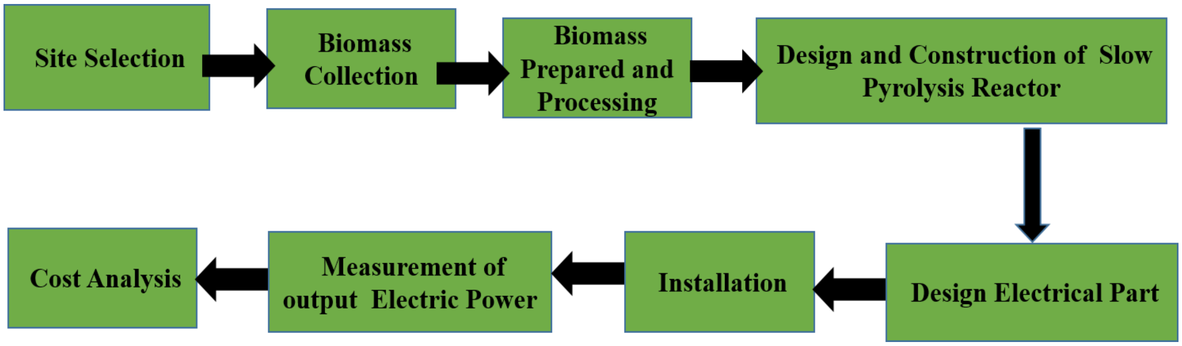

Figure 1. Work Flowchart

Site selection is very important and it has done at the initial stage of the project. The place of experimental setup is far away from locality because of safety for human beings and other living animals. Fire extinguisher must be ensured at the place of experimental hall.

Collection of Biomass: Biomass refers to organic matter derived from plants and animals, representing a renewable and sustainable energy resource. It stores solar energy through photosynthesis, whereby plants convert sunlight into chemical energy. Upon combustion, the stored chemical energy in biomass is released as heat, which can subsequently be converted into electricity. In Bangladesh, diverse biomass feedstocks are available, including forestry residues, mill by-products, agricultural crops and residues, urban wood and yard waste, dedicated energy crops, chemical recovery fuels, animal manure, industrial by-products, municipal solid waste, and sewage sludge. Figure-2 illustrates the distribution of major biomass sources within the country. In the present study, lignocellulosic biomass—specifically wood chips, pellets, and sawdust—was utilized as the primary feedstock. These woody materials, when combusted, produce a substantial thermal output, which was harnessed for electricity generation.

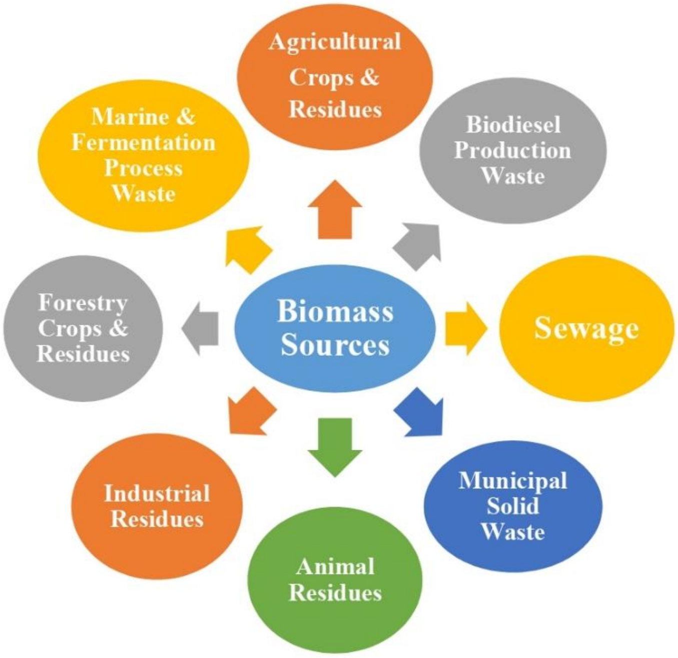

Figure 2. Available Biomass Sources in Bangladesh

Biomass Prepared and Processing: Biomass can be converted into energy and value-added products through six fundamental processing technologies:

a) Direct combustion (for power)

b) Anaerobic digestion (for methane-rich gas)

c) Fermentation (of sugars for alcohols)

d) Oil exaction (for biodiesel)

e) Pyrolysis (for biochar, gas, heat, and oils)

f) Gasification (for carbon monoxide and hydrogen-rich syngas).

These primary conversion technologies may subsequently be integrated with various secondary treatments—such as stabilization, dewatering, upgrading, and refining—depending on the intended end-use products. Biomass feedstocks in nature exhibit substantial heterogeneity in terms of chemical composition, physical properties, toxicity levels, and calorific value. The quality and characteristics of a given feedstock are therefore critical parameters in determining the most appropriate valorization pathway. While energy recovery efficiency is generally considered the principal criterion for selecting a processing route, factors such as economic feasibility and market viability often exert a stronger influence on the commercialization and large-scale deployment of emerging technologies. In the present work, since the target output is thermal energy, slow pyrolysis was selected as the biomass conversion technology, as illustrated in Figure 3.

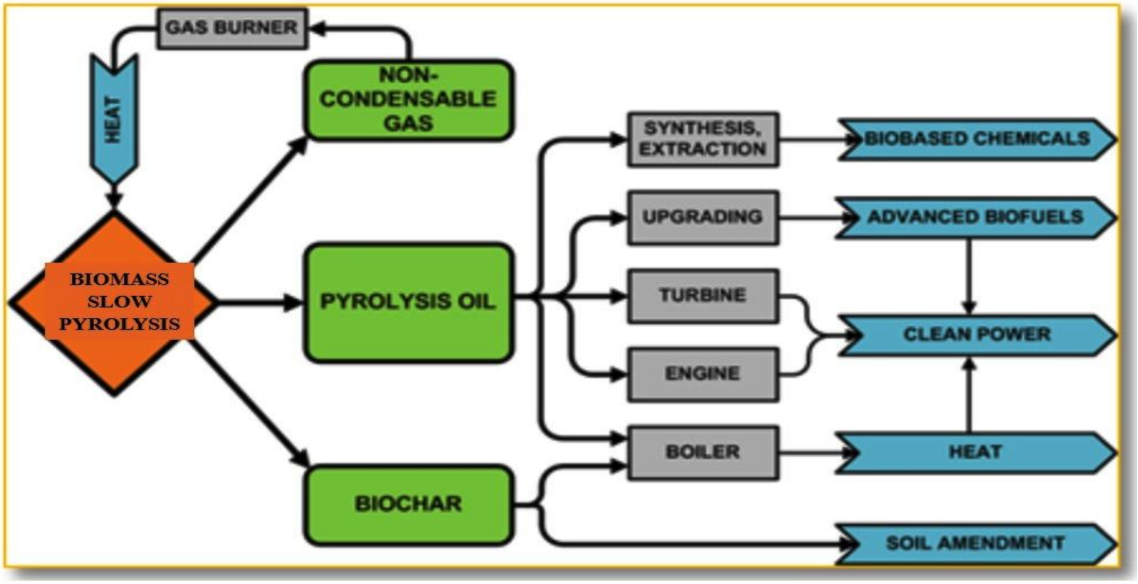

Figure 3. Pyrolysis Procedure from input to output

Slow pyrolysis is a thermochemical conversion process that involves the thermal decomposition of lignocellulosic and other organic feedstocks at moderate temperatures (400–600 °C) under an inert or oxygen-limited atmosphere. Unlike fast pyrolysis, which prioritizes liquid bio-oil production, slow pyrolysis is optimized for maximum biochar yield, with significant fractions of syngas and condensable vapors as co-products. The process kinetics are governed by heating rate (<10 °C/min) and prolonged residence time (minutes to hours), enabling extensive secondary reactions and structural reorganization of carbonaceous matrices.

At the molecular level, slow pyrolysis induces depolymerization, dehydration, decarboxylation, and aromatization of hemicellulose, cellulose, and lignin. Hemicellulose decomposes primarily between 200–350 °C, cellulose between 315–400 °C, and lignin exhibits a broad degradation range up to 600 °C, yielding phenolic compounds and highly recalcitrant char structures. The resultant biochar possesses high carbon content, significant porosity, and surface functionality, making it a versatile material for soil amendment, carbon sequestration, and electrochemical applications.

The energy-rich syngas (CO, H_2, CH_4, and light hydrocarbons) can be directly combusted for heat and power or reformed into higher-value fuels. Condensable vapors yield bio-oil, though with higher oxygen content and lower stability compared to fast pyrolysis oils. Process optimization requires controlling parameters such as feedstock particle size, moisture content, reactor configuration (fixed-bed, rotary kiln, auger, or fluidized-bed), and gas residence time.

Slow pyrolysis contributes to a circular bio-economy by converting agricultural residues, forestry wastes, and organic by-products into renewable energy carriers while simultaneously sequestering stable carbon in biochar. This dual role aligns with global efforts to mitigate greenhouse gas emissions, enhance soil fertility, and advance sustainable energy technologies. Consequently, slow pyrolysis represents a pivotal strategy in biomass valorization and climate change mitigation frameworks.

Design, Construction and working Mechanism of a slow Pyrolysis Reactor

The reactor represents the central unit of a slow pyrolysis system, acting as the dominant factor influencing process efficiency, product yield, and quality. Due to its pivotal role, a wide range of reactor designs have been developed to optimize heat transfer, residence time, and scalability, while addressing the limitations of traditional configurations. Commonly employed designs include fixed-bed, fluidized-bed, auger, rotary kiln, and screw reactors, each offering distinct advantages depending on feedstock properties and targeted end products. Beyond the reactor itself, the process chain typically incorporates biomass reception, storage, and handling, as well as pre-treatment steps such as drying and particle size reduction, followed by product collection, storage, and—where applicable—upgrading or refining. In the present work, a novel reactor configuration has been designed, integrating slow pyrolysis with a power generation unit, as presented in Figure- 4.

The parameters for the reactor design:

(a) Melting point (MP) of the substance: If MP is high, substance easily vaporizes & more heat is obtained.

(b) Density: If density is lower, substance easily vaporizes & more heat is obtained.

(c) Quality of substance: More is quality, more is the yield of heat.

(d) Moisture content: More is moisture; more heat is obtained.

(e) Reactor Temp: More is the reactor temp; more is the heat.

(f) Heating rate: More is the heating rate; more is the heat.

(g) Reactor size: There is an optimum for the reactor size to get maximum heat (4 ft ×4 ft).

(h) Feed rate: Feed rate is given according to the demand for the heat.

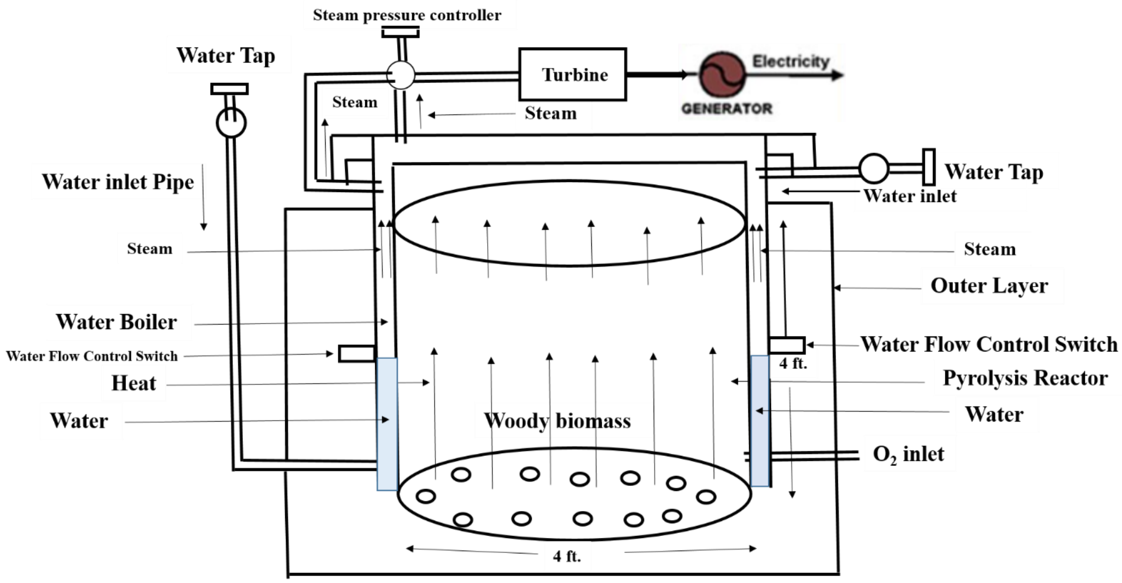

Figure 4. A new design of biomass slow pyrolysis integrated with the power generation system.

In a slow pyrolysis reactor, the biomass feedstock undergoes controlled thermal degradation in an inert or oxygen-limited environment, typically between 300 °C and 600 °C, with prolonged vapor and solid residence times. The mechanism involves multiple overlapping stages: (i) drying, where physically bound moisture is removed below 150 °C; (ii) devolatilization**,** where hemicellulose decomposes (~200–350 °C), cellulose depolymerizes (~300–400 °C), and lignin gradually breaks down (~250–500 °C), producing volatile vapors, condensable tars, and permanent gases; and (iii) carbonization**,** in which solid residues undergo further aromatization, polymerization, and condensation to form a stable, carbon-rich biochar.

Heat transfer occurs primarily through conduction and convection, while mass transfer drives the release and diffusion of volatiles through the porous biomass matrix. The overall process kinetics depend strongly on heating rate, particle size, reactor geometry, and inert gas flow. In slow pyrolysis, the low heating rate (≤10 °C/min) promotes secondary char-forming reactions, minimizing volatile yield. The endothermic primary decomposition and exothermic secondary char stabilization achieve a quasi-steady thermal balance. Consequently, slow pyrolysis maximizes solid char yield (≈30–40 wt%) and produces limited bio-oil and syngas fractions, making it suitable for biochar production, carbon sequestration, and soil amendment applications.

The operational mechanism for generating electricity from biomass via slow pyrolysis is an integrated thermochemical process that transforms solid organic matter into usable power through carefully controlled thermal decomposition, with the core components of a generator and turbine being central to the final energy conversion stage. The process begins with biomass feedstock preparation, where materials such as wood chips, agricultural residues (e.g., straw, rice husks), or dedicated energy crops are sourced, dried to a moisture content typically below 15-20% to enhance efficiency, and size-reduced to ensure uniform heat transfer (Mohan, Pittman, & Steele, 2006). The prepared biomass is then fed into an oxygen-limited slow pyrolysis reactor—such as a rotary kiln, screw auger, or fixed-bed unit—where it is subjected to a slow heating rate (0.1 to 50°C/min) and long residence times (minutes to several hours) at moderate temperatures ranging from 350°C to 550°C (Bridgwater, 2012). Under these conditions, the biomass undergoes devolatilization, breaking down its main constituents (cellulose, hemicellulose, and lignin) into three primary products: a solid biochar, a liquid bio-oil, and a non-condensable syngas (Lehmann & Joseph, 2015). The syngas, composed mainly of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and carbon dioxide (CO_2), is drawn off and passed through a condensation system where heavier, condensable vapors are cooled into bio-oil. The remaining cleaned syngas is then utilized for energy production; it can be combusted directly in a boiler to generate high-pressure steam. This steam drives a Turbine (typically a steam turbine), which converts the thermal energy into mechanical rotational energy. The spinning turbine is directly coupled to a generator, which operates on the principle of electromagnetic induction to convert this mechanical energy into Electricity (Bridgwater & Peacocke, 2000). Alternatively, the syngas can be fired in a gas engine or a gas turbine for direct mechanical drive, similarly coupled to a generator. The bio-oil co-product can also be combusted in a similar manner to supplement fuel input, enhancing the overall energy output of the system. A portion of the syngas or bio-oil is often used to provide the process heat for the pyrolysis reactor itself, creating a more energy-self-sufficient operation (Brown, 2011). The solid biochar, being a stable carbon-rich material, is collected as a valuable by-product for soil amendment or carbon sequestration, adding to the process's sustainability. Thus, through the sequential stages of feedstock preparation, slow pyrolysis, product separation, and the final conversion of chemical energy in the gases/liquids into mechanical energy via a turbine and then into electrical energy via a generator, the system effectively accomplishes the transformation of biomass into a renewable source of Electricity (Yaman, 2004).

Electrical System Design

The electrical design is very important of this experimental work. From the pyrolysis reactor, it is created huge amount of heat, and the flow of water inside the second layer of reactor (Figure-4) is continuous produced steam. This steam is used to generate electricity. For this purpose, a steam turbine and a generator is connected as shown in the Figure-5. The developed system generates a maximum electrical power output of 15 W that can be classified as a low-power generation unit. In spite of its limited capacity, the generated power is sufficient to operate various low-power electronic and communication devices, such as LED lighting units, Wi-Fi routers, smartphone chargers, tablet computers, and Wi-Fi/IP cameras, all of which typically require less than 15 W during normal operation. This level of output is mostly suitable for experimental and research-oriented applications, where the primary objective is to evaluate the feasibility of converting waste heat or secondary thermal energy into usable electrical power. In this experimental setup, the steam produced from the pyrolysis reactor is utilized to drive a small turbine, which in turn powers a DC generator. The generated DC current can either be used to operate energy-efficient devices directly or stored in small-scale battery systems for later use. This study thus shows the potential of micro-scale power generation from thermal energy recovery processes, highlighting its relevance in distributed renewable energy systems, energy harvesting, and sustainable laboratory-scale power applications.

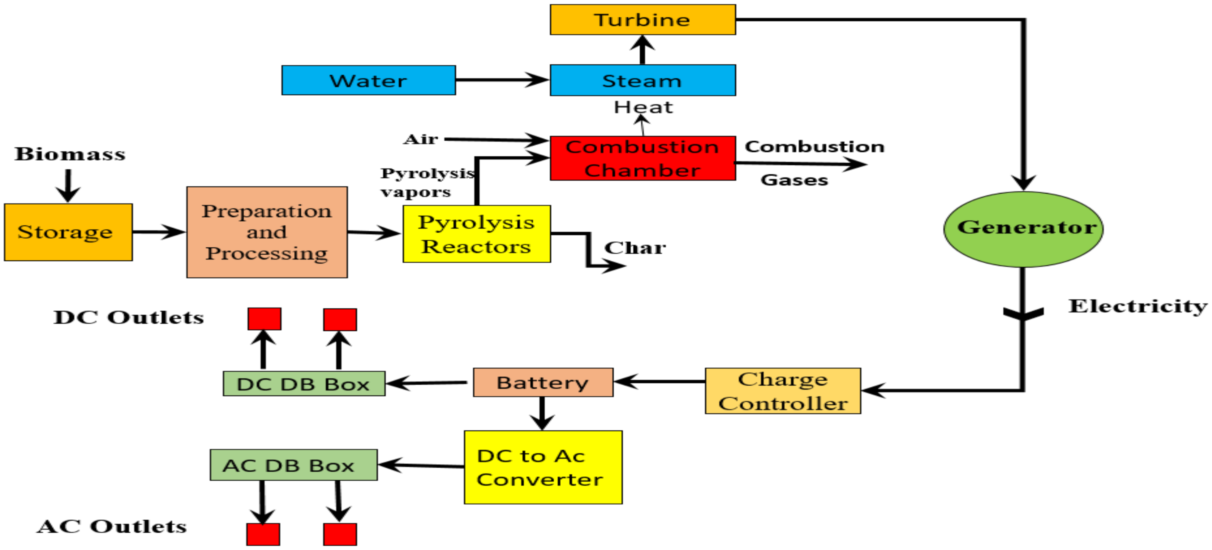

Figure 5. Biomass to electricity production procedure.

Slow Pyrolysis Installation

After constructed slow pyrolysis reactor and designed electrical parts then the entire devices were installed at the experimental hall. At the beginning it was checked whether the devices run well or not. Finally, it was run for the experimental purpose and generated electricity properly (Figure-6).

Figure 6. Installation of Pyrolysis reactor combined with electrical part.

Results and Discussions

Upon the successful installation of the slow pyrolysis system, a novel electricity generation framework has been established, capable of delivering small-scale, low-power applications from woody biomass via thermal energy. This innovation represents a unique advancement in renewable energy technology, enabling direct electricity production from lignocellulosic biomass and contributing to the intellectual property domain through patentable biomass technologies. This scientific breakthrough redefines the biomass utilization paradigm—transforming “biomass disposal into electricity”—while promoting sustainable energy development. The operational process exhibited thermal transitions with initial and final temperatures ranging from approximately 400 °C to 600 °C. According to the Figure-7, the product yield distribution of biomass pyrolysis is strongly influenced by reactor temperature. At 450 °C, biochar yield is highest (≈38 wt.%), while syngas remains relatively low (≈28 wt.%). At the optimized 500 °C, product distribution becomes more balanced, with 32 wt.% biochar, 38 wt.% bio-oil, and 30 wt.% syngas, enabling efficient energy recovery. At higher temperatures (550 °C), biochar decreases further to ≈28 wt.%, while syngas production rises significantly to ≈42 wt.% due to enhanced cracking reactions, though bio-oil yield declines. These results demonstrate the trade-off between solid carbon retention and gaseous fuel generation, underscoring the importance of temperature optimization in reactor design.

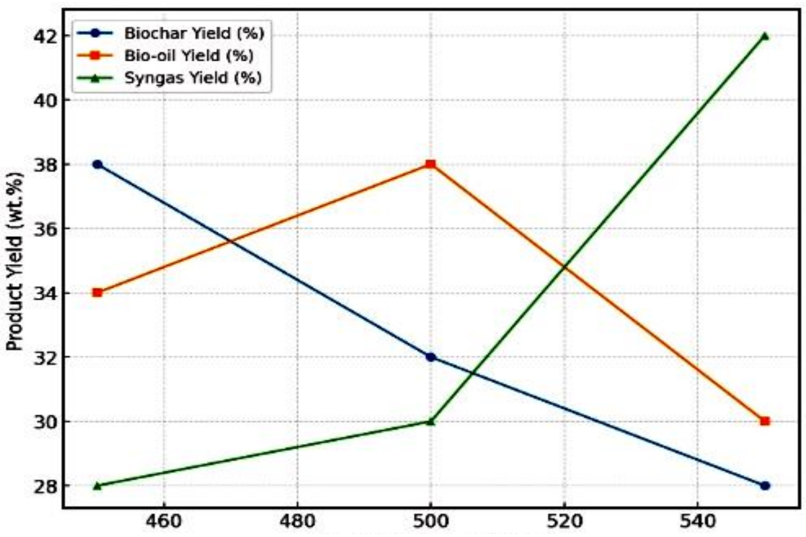

Figure 7. Product Yield Distribution at Different Pyrolysis Temperatures

Figure-8 demonstrates that the electrical power output of the pyrolysis system shows a direct correlation with reactor temperature. The amount of heat transferred is directly proportional to the temperature change. At 450 °C, the syngas fraction was insufficient to sustain stable combustion, resulting in a modest output of 8 W. At the optimized 500 °C, balanced gas production enhanced combustion efficiency, generating a stable output of 15 W. Further increasing the temperature to 550 °C slightly improved output to 17 W, attributed to higher syngas yields from secondary cracking reactions.

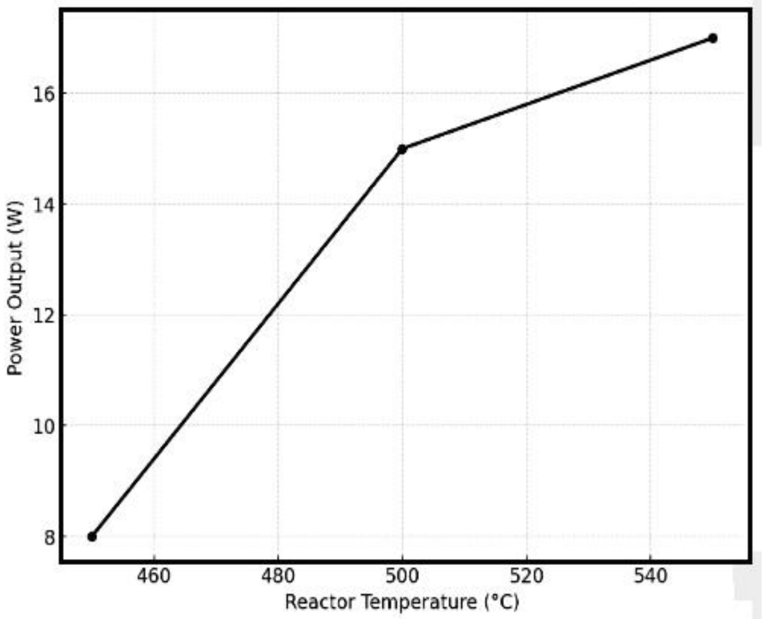

Figure 8. Electrical Power Output vs. Reactor Temperature

However, excessive thermal stress at elevated temperatures may compromise reactor durability, indicating that 500 °C offers the most reliable balance between yield and power generation. The power output of the pyrolysis-driven biomass system is primarily governed by the quantity and composition of syngas produced during thermochemical conversion. At optimal conditions (500 °C), the reactor generated a stable 15 W, with an electrical efficiency of 12.4%. This performance reflects the effective combustion of CO, H_2, and CH_4 fractions in the micro-turbine. At lower temperatures, reduced gas yield limited output, while higher temperatures (550 °C) increased output slightly to 17 W but introduced material stress concerns. Thus, power output optimization requires balancing gas yield enhancement with reactor durability and long-term operational stability.

The voltage and current characteristics of the pyrolysis-based power system reflect the dynamic behavior of syngas combustion, heat produced by system, steam pressure and generator stability. At the optimized operating point (500 °C)**,** the system delivered an output voltage of approximately 12 V (DC) with a corresponding current of 1.25 A(DC)**,** yielding the net power of 15 W.

At lower temperatures, reduced gas production caused fluctuations in both voltage and current, leading to unstable output. Conversely, at 550 °C, voltage and current increased slightly due to higher syngas yield, but thermal stress posed risks to stable operation. This highlights the critical role of thermal management in achieving consistent electrical performance. The alternating current (AC) output of the system can be obtained through an inverter, delivering a voltage in the standard household range of 110–220 V AC**.** Correspondingly, the output current is estimated within the range of 0.07–0.14 A, as derived from the power relation I=P/V. For instance, at a rated output of 15 W and an operating voltage of 220 V, the calculated current is approximately 0.068 A**,** thereby validating the expected current range. This output profile confirms the feasibility of the system for low-power residential and small-scale electrical applications.

The frequency stability of the pyrolysis-driven biomass power system is a crucial indicator of electrical quality and generator performance. During optimized operation at 500 °C, the system maintained a steady frequency of 50 Hz, consistent with standard grid requirements. At lower temperatures, insufficient syngas production caused minor fluctuations, occasionally dropping below 49 Hz due to unstable combustion. At higher temperatures (550 °C), the increased syngas fraction improved generator performance but introduced transient spikes above 51 Hz. These deviations, though small, emphasize the need for effective control systems to stabilize frequency, ensuring reliable integration with micro-grids or standalone rural electrification systems.

The power factor of the pyrolysis-based biomass energy system indicates how effectively electrical power is converted into useful work. At the optimized operating temperature of 500 °C, the system achieved a power factor of approximately 0.92, signifying efficient utilization of active power with minimal reactive losses. At lower temperatures, reduced syngas yield led to unstable combustion, lowering the power factor to around 0.85. Conversely, at higher temperatures (550 °C), increased syngas production slightly improved power factor but raised concerns of thermal stress. Maintaining a high power factor is essential for minimizing energy losses and ensuring reliable integration with electrical loads.

The electrical efficiency of the pyrolysis-driven biomass conversion system reflects the ratio of electrical energy generated to the total energy content of the feedstock. At the optimized operating temperature of 500 °C, the system achieved an efficiency of 12.4%, consistent with reported values for small-scale pyrolysis-to-electricity processes. Lower operating temperatures limited syngas availability, reducing efficiency to below 10%. Although higher temperatures (550 °C) increased gas yield and slightly improved efficiency, they also introduced reactor durability concerns. Therefore, maintaining moderate operating conditions is crucial to achieving a balance between stable power generation, efficiency, and long-term system sustainability.

The electrical efficiency of 5–10% in a pyrolysis-driven biomass energy system can be explained mathematically based on how the total biomass energy is distributed among its product streams. Let the total energy content of biomass be E_b (100%). During pyrolysis, only a portion of this energy—denoted by

f_g is converted into the chemical energy of syngas, typically 20–30% of E_b The remaining energy is retained in biochar (30–40%) and bio-oil (20–30%), which are not directly converted into electricity. The syngas produced is then used in a gas engine or generator with an efficiency η_{eg}*of* about 25–35%.

Hence, the overall electrical efficiency can be expressed as: $\eta_{elec}= f_g \times \eta_{eg}$

For example, if f_g=0.20 and η_{eg}=0.25, then η_{elec}=0.20×0.25= 0.05(5%). If f_g=0.30 and η_{eg}=0.30, then η_{elec}=0.30×0.35= 0.105(10%).

These values demonstrate that only a small portion of the biomass energy is ultimately converted into electricity because of thermal losses, incomplete gas utilization, and limited generator efficiency, while the rest remains stored in biochar and bio-oil. This results in an overall electrical efficiency typically ranging between 5% and 10%.

The stability and quality of electricity generated from the pyrolysis-based biomass system are governed by the consistency of syngas production and generator response. At the optimized 500 °C condition, the system delivered steady voltage (~12 V), frequency (50 Hz), and power output (15 W) with minimal fluctuations, ensuring reliable performance. At lower temperatures, unstable combustion led to irregular voltage and frequency drops, reducing power quality. Higher temperatures (550 °C) improved output but introduced transient fluctuations due to excessive cracking reactions. Overall, system stability depends on maintaining controlled operating conditions, efficient thermal management, and proper generator synchronization for high-quality electricity.

The system delivers an energy output of 15 watt-hours (Wh) over a one-hour operating period, calculated from the relation $E=P\times t$, where $P=15\ W$ and $t=1\ h$. This energy level is appropriate for powering low-load electrical devices, including light-emitting diodes (LEDs), environmental monitoring sensors, miniature-cooling fans, and the charging of small-capacity rechargeable batteries. Such an output profile highlights the applicability of the system for distributed, low-power energy demands, particularly in decentralized and off-grid contexts where compact renewable energy solutions are essential. Table-1 provides a comprehensive summary of the performance outputs obtained from this technology.

Table 1. The results of this technology are systematically summarized.

Parameter	Specification / Range	Notes
Power Output (P)	15 W	Continuous or peak, depending on generator design
Voltage (V)	5–12 V DC or 110–220 V AC	Depends on generator type (DC from thermoelectric, AC via inverter)
Current (I)	1.25–3 A (DC) or 0.07–0.14 A (AC)	Calculated from P = V × I
Frequency (f)	50 Hz (AC), 0 Hz (DC)	Standard grid-compatible frequency in Bangladesh
Power Factor (PF)	0.8–1.0	AC systems only; DC systems assumed near unity
Electrical Efficiency	5–10%	Fraction of biomass energy converted to electricity
Energy per Hour (E)	15 Wh	Energy available for low-power devices like LED bulb, Wi-Fi router (home use), Smartphone charger, Tablet, Wi-Fi camera / IP camera.
Output Stability	Fluctuating without regulation	Requires voltage regulator or capacitor for smoothing
Load Suitability	LEDs, sensors, small fans, battery charging	Small-scale, low-power applications

The scalability of pyrolysis-driven biomass energy conversion is determined by the adaptability of reactor design, feedstock logistics, and integration with existing energy infrastructures. Pyrolysis technology exhibits a high degree of modularity, allowing systems to be scaled from small laboratory units (5–10 kg h^{-1}) to medium pilot plants (50–200 kg h^{-1}) and industrial-scale facilities (>1 t h^{-1}). At each scale, the fundamental process—thermal decomposition of biomass under limited oxygen—remains consistent, though heat transfer dynamics, gas residence time, and reactor wall insulation must be optimized to maintain uniform temperature profiles (Basu, 2018). Scalable designs commonly employ continuous-feed screw or auger reactors equipped with heat recovery units and gas recirculation systems to improve thermal efficiency and process stability (Bridgewater, 2012).

From an economic perspective, the viability of pyrolysis systems depends on both capital investment and operational expenditures. Initial costs include reactor fabrication (mild steel or stainless steel), insulation materials, heat exchangers, and gas-cleaning units, which typically account for 60–70% of total project cost (Demirbas, 2017). Operating expenses involve feedstock preparation, labor, and periodic maintenance. However, the utilization of low-cost or waste biomass—such as rice husk, sawdust, jute stick, or coconut shell—significantly enhances the system's economic return, especially in agricultural regions of Bangladesh where such residues are abundant and underutilized.

Revenue generation arises from multiple product streams. The biochar fraction (30–40 wt%) can be marketed as a soil conditioner, adsorbent, or carbon sequestration material eligible for carbon credits. Bio-oil (20–30 wt%) serves as a substitute for fossil-derived fuel oils in industrial boilers, while syngas (10–20 wt%) can be directly used to generate heat or electricity through gas engines or turbines (Lehmann & Joseph, 2015). Integration of co-generation systems allows partial self-sustainability by recycling syngas for heating, thus reducing external energy input. Studies have reported payback periods ranging from 3 to 5 years for medium-scale plants, with internal rates of return (IRR) exceeding 20% under favorable market and policy conditions (Tripathi et al., 2016).

Additionally, decentralized deployment of modular pyrolysis units enhances energy access in rural areas by converting locally available biomass into useful energy and soil-improving byproducts. When supported by renewable energy incentives, feed-in tariffs, or carbon credit mechanisms, pyrolysis-driven biomass systems become economically and environmentally sustainable. Therefore, this research's reactor design and power assessment demonstrate a scalable, cost-effective pathway for clean energy production and waste valorization in developing regions.

Conclusions

We have designed and constructed a new pyrolysis reactor, which has worked as a slow pyrolysis process to generate electricity in this research work. This work has developed a technology to convert heat to electricity by using slow pyrolysis method, which can be play an important role in the area of power development. By this technology, it is possible to produce average 15-watt electric power that can be continued or peak, depending on generator design and can be added national grid by an on grid inverter. This power can use for small-scale, low-power applications. For this output, it needs maximum pressure of the steam. The electrical efficiency of this system is around 5-10% (Fraction of biomass energy converted to electricity). Power Factor (PF) for AC systems only is 0.8–1.0 whereas DC systems assumed near unity. These results can be used as the base line data, and further study is required to find out higher efficiency of this method. Economic evaluation suggests that, given an average energy output of 15 W and potential for scale-up, the system demonstrates moderate cost-effectiveness, with payback periods highly sensitive to feedstock availability, energy pricing, and efficiency optimization. Energy is a critical driver of national economic and societal development. In Bangladesh, rising population and economic expansion have intensified energy demand, amplifying dependence on imported fossil fuels and associated economic vulnerabilities. This study highlights the bidirectional linkage between energy availability and economic growth, emphasizing the need for sustainable, cost-effective alternatives. Biomass-based renewable energy emerges as a viable solution, offering environmentally benign and economically feasible electricity generation. Implementation of such technologies can mitigate fossil fuel reliance, reduce environmental impacts, and contribute to long-term energy security and sustainable economic development.

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References

Akhtar, J., & Amin, N. A. S. (2011). A review on operating parameters for optimum liquid oil yield in biomass pyrolysis. *Renewable and Sustainable Energy Reviews, 15*(4), 1615–1624. https://doi.org/10.1016/j.rser.2010.11.054

Basu, P. (2018). *Biomass gasification, pyrolysis and torrefaction: Practical design and theory* (3rd ed.). Academic Press. https://doi.org/10.1016/C2016-0-04997-9

Bridgwater, A. V., & Peacocke, G. V. C. (2000). Fast pyrolysis processes for biomass. *Renewable and Sustainable Energy Reviews*, *4*(1), 1-73. https://doi.org/10.1016/S1364-0321(99)00007-6

Bridgwater, A. V. (2003). Renewable fuels and chemicals by thermal processing of biomass. *Chemical Engineering Journal, 91*(2–3), 87–102. https://doi.org/10.1016/S1385-8947(02)00142-0

Bridgwater, A. V. (2012). Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy, 38*, 68–94. https://doi.org/10.1016/j.biombioe.2011.01.048

Brown, T. R., Wright, M. M., Brown, R. C., & Hu, G. (2011). Review of cellulosic biomass conversion technologies for ethanol production. *Renewable and Sustainable Energy Reviews, 15*(1), 564–579. https://doi.org/10.1016/j.rser.2010.09.035

Brown, R. C. (2011). Thermochemical Processing of Biomass: Conversion into Fuels, Chemicals and Power. John Wiley & Sons.

Butler, E., Devlin, G., Meier, D., & McDonnell, K. (2011). A review of recent laboratory research and commercial developments in fast pyrolysis and upgrading. *Renewable Energy, 36*(2), 632–638. https://doi.org/10.1016/j.renene.2010.07.004

Cherubini, F., & Ulgiati, S. (2010). Crop residues as raw materials for bioenergy and biomaterials production: Energy analysis and environmental impacts. *Applied Energy, 87*(1), 47–57. https://doi.org/10.1016/j.apenergy.2009.05.009

Demirbas, A. (2004). Combustion characteristics of different biomass fuels. *Energy Conversion and Management, 45*(5), 651–671. https://doi.org/10.1016/j.enconman.2003.09.004

Demirbas, A. (2007). Progress and recent trends in biofuels. Progress in Energy and Combustion Science, 33(1), 1–18. https://doi.org/10.1016/j.pecs.2006.06.001

Demirbas, A. (2017). *Pyrolysis and torrefaction of biomass and waste*. Elsevier. https://doi.org/10.1016/C2016-0-02061-0

Garcia-Nunez, J. A., Garcia-Perez, M., & Adams, T. A. (2017). Pyrolysis of biomass: Energy and chemicals production. *Bioresource Technology, 223*, 263–272. https://doi.org/10.1016/j.biortech.2016.10.047

Huang, Y. F., Chang, C. C., Chen, W. H., & Lin, C. Y. (2016). Bio-oil production from fast pyrolysis of lignocellulosic biomass: Effects of temperature and biomass type. ***Energy, 113***, 631–642. https://doi.org/10.1016/j.energy.2016.07.093

Huber, G. W., Iborra, S., & Corma, A. (2006). Synthesis of transportation fuels from biomass: Chemistry, catalysts, and engineering. *Chemical Reviews, 106*(9), 4044–4098. https://doi.org/10.1021/cr068360d

Lehmann, J., & Joseph, S. (Eds.). (2015). *Biochar for environmental management: Science, technology and implementation* (2nd ed.). Routledge. https://doi.org/10.4324/9780203762264

McKendry, P. (2002). Energy production from biomass (part 1): Overview of biomass. *Bioresource Technology, 83*(1), 37–46. https://doi.org/10.1016/S0960-8524(01)00118-3

Mohan, D., Pittman, C. U., & Steele, P. H. (2006). Pyrolysis of wood/biomass for bio-oil: A critical review. *Energy & Fuels, 20*(3), 848–889. https://doi.org/10.1021/ef0502397

Tripathi, M., Sahu, J. N., & Ganesan, P. (2016). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and Sustainable Energy Reviews, 55*, 467–481. https://doi.org/10.1016/j.rser.2015.10.122

Venderbosch, R. H., & Prins, W. (2010). Fast pyrolysis technology development. *Biofuels, Bioproducts and Biorefining, 4*(2), 178–208. https://doi.org/10.1002/bbb.198

Yaman, S. (2004). *Pyrolysis of biomass to produce fuels and chemical feedstocks*. Energy Conversion and *Management*, *45*(5), 651–671. https://doi.org/10.1016/S0196-8904(03)00177-8

Zhang, Y., Tang, H., Chen, X., Zhang, Z., & Li, J. (2020). Recent advances in catalytic fast pyrolysis of biomass for bio-oil production. *Energy, 190*, 116430. https://doi.org/10.1016/j.energy.2019.116430