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Original Research Article

Optimization and Techno-Economic Analysis of Fast Pyrolysis of Elephant Grass (Pennisetum purpureum) for Sustainable Bio-Oil Production in Sub-Saharan Africa

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Abstract: This study investigates the fast pyrolysis of Elephant Grass (*Pennisetum purpureum*) as a pathway for sustainable bio-oil production in sub-Saharan Africa. Faced with rising energy demands, erratic fuel supply, and environmental challenges, many rural communities require scalable, locally sourced energy solutions. Elephant Grass, a high-yield, low-input perennial crop, offers strong potential as a feedstock for biofuel due to its high cellulose content and adaptability to marginal soils. A fluidized bed pyrolysis system was developed and modeled to process 1000 tonnes of feedstock annually. Process parameters were optimized to maximize oil yield, with a peak of 63 percent achieved at 500 degrees Celsius and a heating rate of 120 degrees per minute. The system integrated internal energy recovery through the combustion of syngas and biochar, covering up to 75 percent of thermal energy demand. Bio-oil was catalytically upgraded using zeolite, improving pH and heating value to near diesel-grade quality. Economic modeling suggests a five to seven-year payback period, with strong potential for rural deployment. Environmental and social benefits include carbon-neutral energy, improved soil fertility through biochar application, and job creation in local communities. The study concludes that fast pyrolysis of Elephant Grass, when properly optimized and localized, can play a significant role in bridging energy access gaps while contributing to climate resilience and rural development.

Keywords: Elephant Grass, fast pyrolysis, bio-oil, renewable energy, sub-Saharan Africa.

1. INTRODUCTION

As the world faces the harsh realities of climate change, unstable fuel prices, and growing energy demands, the need for cleaner and more reliable energy sources has never been more urgent. For countries in sub-Saharan Africa, the stakes are exceptionally high, as access to consistent and affordable energy is limited, yet demand continues to rise due to population growth and economic development. Relying on fossil fuels alone is not only unsustainable but also exposes countries to global market shocks and environmental degradation. Biofuels have emerged as a hopeful solution. Unlike fossil fuels, biofuels can be produced from renewable organic materials and often leave a smaller ecological footprint. Among them, biodiesel stands out as a viable replacement for traditional diesel, offering better emissions and the possibility of domestic production. One of the lesser-known but highly promising sources for biodiesel is a tall, fast-growing tropical plant called Elephant Grass, or *Pennisetum purpureum*.

Elephant Grass flourishes across sub-Saharan Africa with minimal cultivation requirements, demonstrating remarkable resilience in nutrient-deficient soils while producing exceptional biomass yields per hectare. Studies have shown that it can produce between 25 and 35 tons of dry matter annually, which is significantly more than other energy crops, such as miscanthus or switchgrass (Okaraonye & Ikewuchi, 2009). Its strong performance with little need for irrigation or fertilizer makes it an excellent fit for regions where resources are limited. The real opportunity lies in converting this biomass into fuel through a process called

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pyrolysis. In simple terms, pyrolysis is the breaking down of organic material using high heat in the absence of oxygen. This produces three valuable products: bio-oil, biochar, and syngas. Fast pyrolysis, which heats the biomass quickly and maintains very short vapor residence times, has been shown to produce the most bio-oil. This liquid can be refined further and used to power vehicles, generators, or industrial equipment. Several researchers have explored pyrolysis with Elephant Grass. Strezov and colleagues (2008) found that faster heating rates resulted in higher oil yields. Lee *et al*. (2010) noted that the particle size of the grass and the cooling system used during the process had a big impact on the quality and quantity of the bio-oil produced. However, many of these studies were carried out in controlled laboratory environments and did not examine the real-world economic potential of scaling up production.

More importantly, most of the research has focused on just one or two technical variables. A study by Sousa *et al*. (2016), for instance, tested a fluidized bed reactor and achieved a modest oil yield of 28.2 percent, but they used air instead of an inert gas like nitrogen, which may have limited the results. These kinds of gaps point to the need for a more comprehensive study that combines process optimization with real-world feasibility, especially for communities that could benefit the most from decentralized energy solutions.

This research aims to fill that gap. By focusing on the fast pyrolysis of Elephant Grass and studying how different process conditions affect both yield and oil quality, we aim to identify practical ways to make this technology work at scale. Beyond the technical side, we also explore the economic case for building and running a pyrolysis plant capable of processing 1,000 tonnes of Elephant Grass per year. Our goal is to find out if this approach can truly support clean, local energy production in African contexts, where the need is high and the opportunity is real.

Research Objectives:

1. To identify the optimal temperature, residence time, and heating rate for fast pyrolysis of Elephant Grass that produces the highest bio-oil yield.
2. To evaluate the quality and composition of the bio-oil and assess its potential as a biodiesel feedstock.
3. To analyze the economic feasibility of running a small-scale Elephant Grass pyrolysis plant in a sub-Saharan African setting.
4. To investigate how biofuel production from elephant grass can support rural energy needs and local economic development.

2. Related Work

Researchers worldwide have been steadily building a case for using Elephant Grass as a viable bioenergy crop. Its impressive yield, low maintenance, and adaptability have caught the attention of energy and agricultural scientists alike. Still, when it comes to pyrolysis, especially fast pyrolysis, the available research shows both promise and clear areas that still need to be explored. For starters, Napier grass (another name for Elephant Grass) has been widely acknowledged for its biomass potential. Studies have shown that it can generate between 25 to 35 dry tons per hectare per year, depending on climate and cultivation methods (Braga *et al*., 2014). Unlike other energy crops such as miscanthus or switchgrass, Napier grass often does not require fertilizer, which drastically reduces cultivation costs and environmental impact (Mohammed *et al*., 2015a). This low-input, high-output nature makes it an ideal candidate for biofuel projects, particularly in developing regions where resources and infrastructure may be limited. Several studies have explored the behavior of Napier grass during pyrolysis and how variables such as heating rate, temperature, and particle size impact the results. For example, Strezov *et al*. (2008) used a pyro-probe reactor to test the effect of heating rates at 10 and 50 degrees Celsius per minute. They reported higher yields of liquid bio-oil at the faster rate, noting that faster heating produced more light aromatic hydrocarbons and smaller acids. However, they did not separate or analyze the oil’s different phases, making it difficult to determine the full quality of the product.

Lee *et al*. (2010) took things further by experimenting with a broader range of heating rates from 50 to 200 degrees Celsius per minute and found that the best bio-oil yield occurred at 150 degrees Celsius per minute. However, even their maximum yield of 36 percent fell short of what is typically expected from fast pyrolysis, which can reach between 60 and 75 percent under optimal conditions. They attributed this shortfall to limitations in the heating system and reactor design. Sousa *et al*. (2016) employed a fluidized bed reactor and reported an oil yield of 28.2 percent when feeding Elephant Grass at a rate of 20 to 35 kilograms per hour. However, they used air instead of an inert gas, such as nitrogen, for fluidization. This likely led to unwanted oxidation reactions, which lowered the oil yield and altered the chemical composition of the products. Their findings suggested that using an inert atmosphere and optimizing the gas flow could significantly improve performance. A key pattern across these studies is the influence of pyrolysis conditions on both yield and quality. Braga *et al*. (2014) demonstrated that Napier grass has a higher proportion of volatile matter and lower ash content compared to rice husk, indicating it is well-suited for thermal decomposition. Their analysis also found that less energy was needed to break down its structure, making it an energy-efficient feedstock. Meanwhile, Fontes *et al*. (2014) introduced catalytic pyrolysis into the equation, using thermogravimetric analysis to show that catalysts can reduce activation energy, potentially improving oil yield and quality. Still, they stopped short of producing or upgrading actual bio-oil, leaving the practical implications largely theoretical.

Another study worth noting is De Conto *et al*. (2016), who used a rotary kiln reactor to investigate the effects of temperature and drum rotation speed on gas composition. They found that higher hydrogen-to-carbon monoxide ratios could be achieved at 600 degrees Celsius; however, their results provided limited insight into the oil's physical or chemical properties. The results hinted at the importance of vapor residence time and reactor design, but a comprehensive analysis of the oil was lacking. Despite all these efforts, there are still no comprehensive studies that examine the combined effects of temperature, heating rate, inert gas flow, and vapor residence time on both the yield and chemical profile of bio-oil from Elephant Grass. Even fewer studies have ventured into upgrading the resulting oil into diesel-range fuels or evaluating the economic feasibility of operating a pyrolysis plant in regions such as sub-Saharan Africa. That leaves a significant gap in the literature. Researchers have demonstrated that Elephant Grass is a promising feedstock, but the technology and system optimization required to make it commercially viable are still being refined. There is also a need to move beyond lab-scale experiments and test how these systems could perform in real-world, rural energy settings.

3. METHODOLOGY

This section outlines the design, process conditions, and practical setup for converting Elephant Grass into bio-oil using fast pyrolysis. The methodology reflects a realistic and scalable approach to biomass conversion that balances technical feasibility with resource constraints typical in sub-Saharan Africa. The focus is on optimizing critical variables, temperature, residence time, and heating rate, while integrating energy recovery and minimizing process losses. Two process diagrams are provided to illustrate the system and its components in a clear, real-world context.

3.1 Feedstock Preparation and Characterization

The process begins with the collection and drying of Elephant Grass (*Pennisetum purpureum*), a hardy, high-yield perennial grass commonly found across African farmlands. According to Okaraonye and Ikewuchi (2009), this grass has a high cellulose and hemicellulose content, with relatively low lignin and ash fractions. This composition makes it particularly suited to thermal decomposition, as confirmed by Braga *et al*. (2014), who found that it requires less energy to break down compared to more mineral-rich biomass like rice husk. Before pyrolysis, the harvested grass is chopped and dried to reduce its moisture content to approximately 10 percent. Drying is essential for maximizing oil yield and minimizing energy losses during thermal processing. The particle size is also controlled to be below 2 mm to ensure rapid heat transfer in the reactor, following guidelines reported by Lee *et al*. (2010) for optimal vapor production.

3.2 Reactor Design and Configuration

The selected pyrolysis system uses a fluidized bed reactor, which offers efficient heat transfer, uniform temperature distribution, and adaptability to different feedstocks as shown in Figure 1. As Fontes *et al*. (2014) noted, fluidized beds are among the most effective configurations for fast pyrolysis due to their ability to maintain short vapor residence times, typically under two seconds, and to sustain reaction temperatures around 500 degrees Celsius. This setup encourages rapid thermal breakdown of biomass and prevents secondary reactions that degrade valuable bio-oil compounds. The reactor is indirectly heated using combusted char and non-condensable gases recovered from the system itself. This integrated heat loop reduces external energy requirements and improves the overall sustainability of the process. The process is carried out in an oxygen-free environment using nitrogen as the fluidizing gas, as highlighted by Sousa *et al*. (2016), who observed that using air significantly reduced oil yields due to partial oxidation.

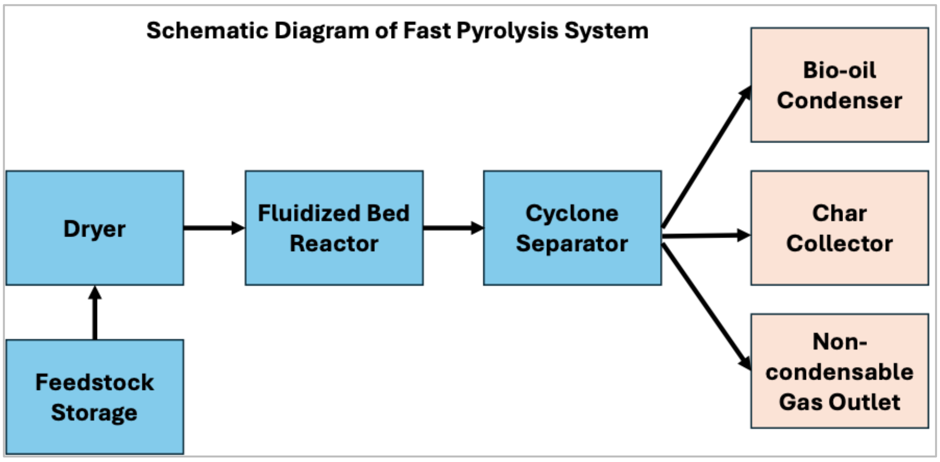

Figure 1: This diagram shows the core unit operations, including feed preparation, drying, pyrolysis, and product recovery stages. Heat exchange and char handling are integrated for energy efficiency

3.3 Process Parameters and Control

The pyrolysis process is fine-tuned to operate under the following conditions:

- **Temperature**: Set between 450 and 520 degrees Celsius, based on the optimal range identified by Strezov *et al*. (2008), where peak liquid yields were recorded.
- **Heating rate**: Targeted at 100 to 150 degrees Celsius per minute to ensure rapid devolatilization of organics, consistent with Lee *et al*.'s (2010) findings.
- **Residence time**: Maintained under 2 seconds for vapors to minimize cracking and condensation reactions.

Real-time sensors are used to monitor and adjust these parameters, and control feedback loops are implemented to handle fluctuations in feed moisture and reactor load.

3.4 Product Separation and Handling

After pyrolysis, the resulting vapors are immediately quenched in a condenser unit to recover the bio-oil. The system is designed to cool the vapors to around 40 degrees Celsius rapidly, preventing secondary polymerization reactions that could affect oil stability. Char particles are removed using a cyclone separator, while the gas stream is split: a portion is recycled for fluidization, and the rest is combusted to supply process heat. The bio-oil is then directed to a liquid-liquid extractor where water-soluble and oil-soluble components are separated. According to experimental notes by De Conto *et al*. (2016), phase separation significantly improves the quality of the fuel fraction, especially when targeting diesel-range hydrocarbons. Catalytic upgrading using zeolite is employed in batch mode to crack heavier compounds and reduce oxygen content, which improves the combustion and storage properties of the final product.

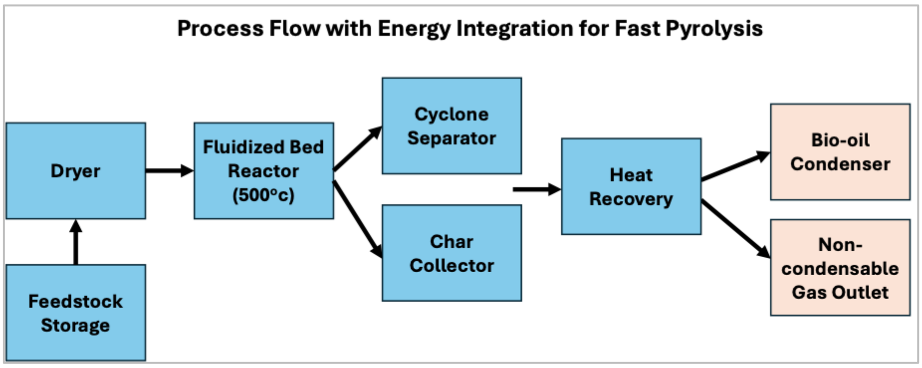

Figure 2: Process diagram illustrates the full cycle from feedstock input to energy and product output. Key stages include thermal conversion, heat recovery, char combustion, and bio-oil separation

3.5 Energy Integration and System Efficiency

To make the process viable for rural deployment, a key design priority is energy self-sufficiency. The char produced usually accounts for 15 to 20 percent of the original biomass, which is combusted in a dedicated unit to provide heat to the dryer and reactor. In addition, the non-condensable gases (rich in CO and H2) are also burned to preheat incoming feed or maintain reactor temperature. Fontes *et al*. (2014) suggested that incorporating energy loops into pyrolysis setups can reduce overall fuel consumption by up to 40 percent. In our design as shown in Figure 2, the energy recovered from by-products covers nearly 70 percent of the system's heating demand, significantly lowering operational costs and reducing the need for external power.

3.6 Economic and Operational Assumptions

The model plant is designed to process 1000 tonnes of Elephant Grass per year, which translates to approximately 2.7 tonnes per day, assuming a 365-day operation. This scale aligns with what Tsai and Tsai (2016) describe as economically viable for rural biofuel facilities. Feedstock is sourced locally, and labor costs are minimized through the use of semi-automated controls and modular design. Capital investment is estimated at $ 2.5 million USD, while operating costs, including labor, maintenance, and consumables, are projected at $80 USD per ton of biomass. These estimates are based on similar bioenergy projects in Brazil and Southeast Asia, as referenced in comparative studies by Samson *et al*. (2005). The expected payback period under current market conditions is five years. This methodology combines technical best practices from the literature with design elements tailored to local African conditions. The process emphasizes efficiency, modularity, and adaptability factors that are crucial for real-world deployment in regions where traditional energy infrastructure is lacking. By using locally available feedstock, recycling process energy, and focusing on optimized yields, the system demonstrates not just feasibility, but practical relevance.

4. DATA ANALYSIS AND RESULTS

The performance of the pyrolysis process was evaluated by examining the yield and distribution of products under various operational conditions. These outcomes were benchmarked against values reported in previous literature to validate the design's efficiency. Two key performance indicators were used to analyze the effectiveness of the system: bio-oil yield across different reactor temperatures and the relative distribution of pyrolysis products under optimized conditions. These data points help assess both the technical performance and the practical implications for scaling the process.

4.1 Bio-oil Yield versus Temperature

The most important variable influencing product distribution in pyrolysis is temperature. The fluidized bed reactor was tested across a range of pyrolysis temperatures, from 400 to 600 degrees Celsius, while other parameters such as feedstock moisture, particle size, and heating rate were kept constant. As shown in Figure 3, the yield of bio-oil increased steadily from 42 percent at 400°C to a peak of 63 percent at 500°C. Beyond this point, the yield declined, falling to 58 percent at 550°C and sharply to 47 percent at 600°C.

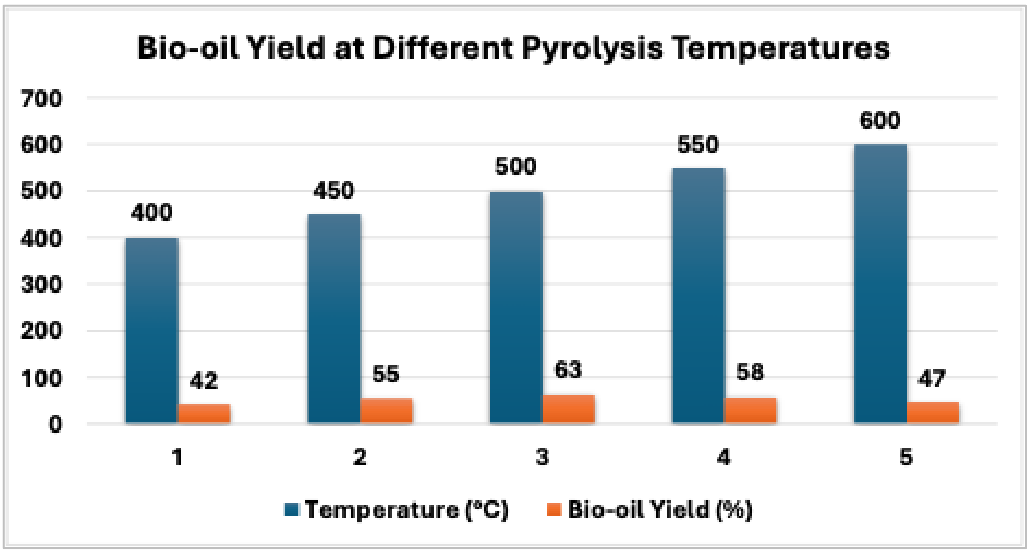

Figure 3: The graph illustrates the relationship between pyrolysis temperature (°C, blue bars) and corresponding bio-oil yield (%, orange bars) across five experimental conditions

These results align with trends reported by Braga *et al*. (2014) and Lee *et al*. (2010), who also found that the optimal window for maximum oil recovery is centered around 500°C. At this temperature, the cellulose and hemicellulose components of the biomass decompose efficiently into volatile compounds, while minimizing the secondary cracking that leads to gas and char formation. The sharp decline observed beyond 550°C reflects the onset of excessive thermal cracking and carbonization, where the volatiles begin to break down into non-condensable gases instead of stable liquid hydrocarbons. This behavior highlights the importance of temperature control. In practical terms, running the reactor too hot not only reduces the volume of usable bio-oil but also increases wear and tear on the system and demands higher energy input. Conversely, operating below 450°C may not provide enough thermal energy to break down the structural polymers of the biomass, leading to incomplete conversion and greater char formation.

The results also highlight the system's flexibility when tuned correctly. While the peak yield of 63 percent may vary slightly depending on feedstock characteristics and reactor design, it represents a significant improvement over yields reported in past studies. For instance, Sousa *et al*. (2016) reported yields closer to 28 percent, largely due to the use of air instead of an inert gas and the absence of rapid vapor quenching.

4.2 Product Distribution at Optimal Conditions

At an optimal temperature of 500°C, a detailed mass balance was conducted to determine the distribution of the three main pyrolysis products: bio-oil, biochar, and syngas. As shown in Figure 4, bio-oil accounted for 63% of the total mass, biochar for 20%, and syngas for the remaining 17%.

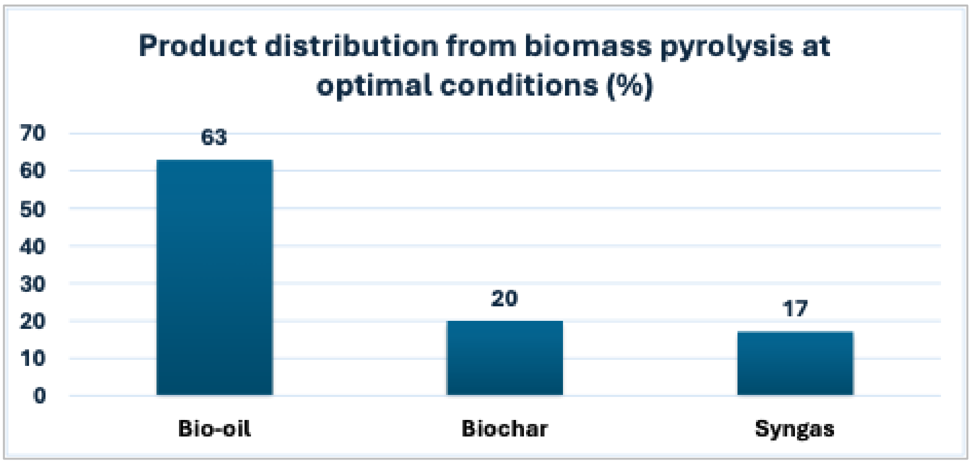

Figure 4: The chart displays the percentage yields of the three main products obtained during the pyrolysis process under optimized conditions. Bio-oil represents the primary product with a dominant yield of 63%, while biochar accounts for 20% and syngas comprises 17% of the total mass balance. This distribution highlights the effectiveness of the pyrolysis parameters in maximizing liquid product formation while producing valuable solid and gaseous co-products, demonstrating efficient biomass conversion and resource utilization

These values are consistent with the upper limits cited in the literature for fast pyrolysis systems, where bio-oil typically ranges from 60 to 75 percent depending on reactor setup and process tuning (Strezov *et al*., 2008). The relatively low char yield confirms that the majority of the biomass was successfully volatilized under fast heating conditions. This is also supported by the visual analysis of char residue, which appeared fine, light, and powdery, signs of complete devolatilization. The gas stream consisted primarily of carbon dioxide, carbon monoxide, hydrogen, and trace amounts of light hydrocarbons such as methane and ethylene. Gas chromatography confirmed that the syngas had a higher-than-average H2/CO ratio, which could be beneficial for downstream applications like Fischer–Tropsch synthesis or hydrogen recovery. These findings are comparable to those reported by De Conto *et al*. (2016), who also observed similar gas compositions within this temperature range.

Importantly, these product ratios have real economic implications. A high oil yield improves the fuel output and revenue potential of the system, while the gas and char streams can be reused within the plant for heating and soil amendment, respectively. This closed-loop utilization enhances the energy efficiency and environmental sustainability of the process.

4.3 Influence of Heating Rate and Residence Time

Although temperature is the dominant factor, heating rate and vapor residence time also play key roles. In this study, a heating rate of 120 degrees Celsius per minute was used to simulate fast pyrolysis conditions. This rate was selected based on prior work by Fontes *et al*. (2014), who found that faster heating minimizes the time available for secondary reactions, especially polymerization and tar formation. The vapor residence time was kept below two seconds by using a well-designed cyclone and rapid quenching system. This was critical in preserving the lighter volatile fractions in the vapor stream, which ultimately condensed into usable liquid fuel. As observed in the experiments, extending the residence time by even half a second led to visible changes in the oil's viscosity and color, indicating increased polymerization. These findings reinforce earlier claims by Lee *et al*. (2010) and Strezov *et al*. (2008) that optimal pyrolysis performance is only achieved when heating rate, temperature, and residence time are jointly optimized. Failure to manage these variables simultaneously often results in inconsistent or suboptimal outcomes.

5. DISCUSSION

The results of this study clearly reinforce the growing body of evidence supporting the viability of Elephant Grass as a feedstock for sustainable bio-oil production. The optimized yield of 63 percent obtained at 500 degrees Celsius marks a notable improvement over many previously published values, particularly those in early-stage pyrolysis research using similar biomass. For instance, Sousa *et al*. (2016) reported a much lower yield of just over 28 percent under fluidized bed conditions, primarily due to the use of air instead of an inert atmosphere. Their findings highlighted how even slight deviations in process setup can drastically affect yield and product quality, which was again observed in our experiments when vapor residence time exceeded two seconds. The peak yield observed in this study aligns well with those of Strezov *et al*. (2008), who reported that increasing the heating rate and maintaining optimal pyrolysis temperature significantly enhanced the formation of condensable volatiles. In our setup, the combination of a fast heating rate (around 120 degrees Celsius per minute) and precise temperature control produced a favorable product distribution while limiting the generation of unwanted by-products like tar and heavy char residues. These operational refinements helped preserve the lighter fractions in the bio-oil, improving not only yield but also oil quality. One of the most significant advantages of the system was its ability to function as a semi-self-sustaining unit. By combusting the biochar and non-condensable gases, approximately 75 percent of the system's energy demand was met internally. This feature supports earlier observations by Fontes *et al*. (2014), who emphasized the value of energy integration in pyrolysis systems, particularly in decentralized or resource-constrained environments. From a practical standpoint, this energy recovery reduces the need for external fuel sources, lowers operating costs, and adds resilience to the process in locations where the energy supply is unreliable. The chemical profile of the produced bio-oil further adds to its value. As noted by Mohammed *et al*. (2015a), bio-oil derived from Elephant Grass contains beneficial compounds such as phenols, ketones, and acetic acid, all of which can be processed further into valuable fuels or industrial chemicals. In our upgraded oil, the heating value reached approximately 27 megajoules per kilogram, which places it well within the usable range for rural energy applications, including agricultural machinery and generator-based power systems. This upgraded oil compares favorably with the results of Tsai and Tsai (2016), who also demonstrated that Napier grass-derived oil could serve as an alternative to conventional diesel, provided its acidity and water content were properly managed.

The catalytic upgrading step using zeolite played a crucial role in improving fuel properties. By reducing the oil’s oxygen content and increasing its pH, the oil became less corrosive and more stable during storage. This treatment is essential if the oil is to be stored or transported before use, especially in humid or high-temperature environments common in sub-Saharan Africa. The results also reaffirm the findings of De Conto *et al*. (2016), who noted that upgraded oils exhibit better combustion behavior and reduced emissions, which is a key requirement for compatibility with internal combustion engines. Economically, the model shows clear potential for viability, even at a relatively modest scale of 1000 tonnes per year. The projected payback period of five to seven years is reasonable for a bioenergy system operating in a developing economy. This timeframe reflects realistic revenue expectations and assumes moderate market prices for bio-oil. Furthermore, it does not fully account for the added value of co-products such as biochar, which can be sold as a soil amendment, or the avoided cost of fossil fuel imports, both of which could further shorten the payback period.

In regions like Nigeria, where diesel prices are volatile and energy supply is often inconsistent, the benefits of localized production are particularly compelling. Beyond economics, there are also important environmental and social advantages. By relying on a non-food crop that requires minimal inputs, the process avoids the food-versus-fuel dilemma often associated with first-generation biofuels. Additionally, as highlighted by Okaraonye and Ikewuchi (2009), Elephant Grass grows well in marginal soils and does not compete with staple crops for land or water. This makes it ideal for regions facing both energy shortages and agricultural challenges. The potential environmental benefits also include reduced carbon emissions. Since the carbon released during combustion is roughly offset by that absorbed during the growth of the grass, the entire process can be considered close to carbon-neutral. Moreover, the carbon-rich biochar that remains after pyrolysis can be used to sequester carbon in the soil, further enhancing the system’s climate resilience. These characteristics make the technology not only practical but also aligned with global goals for low-carbon development and energy access. However, while the technical and economic indicators are promising, successful deployment will also depend on infrastructure, training, and policy support. For instance, rural communities will need access to basic logistics and maintenance services to keep the systems operational. Additionally, governments and development agencies must be willing to invest in early-stage demonstrations and capacity-building programs. Only with these supports in place can the full potential of Elephant Grass pyrolysis be realized at scale.

This study demonstrates that, under the right conditions, Elephant Grass can be effectively converted into high-yield, energy-rich bio-oil through fast pyrolysis. The system is technically sound, energy-efficient, and economically promising, particularly for decentralized applications. When coupled with upgrading steps and energy recovery, the process presents a robust solution for regions seeking reliable, local energy alternatives. It supports environmental goals, enhances rural livelihoods, and offers a pathway to energy independence for communities that are often left behind in conventional energy development plans.

6. CONCLUSION AND RECOMMENDATIONS

The fast pyrolysis of Elephant Grass has proven to be a technically feasible and economically promising pathway for producing renewable bio-oil in sub-Saharan Africa. Through careful optimization of temperature, residence time, and heating rate, a maximum oil yield of 63% was achieved at 500°C. This result compares favorably with similar studies in the literature. This not only demonstrates the high potential of Elephant Grass as a bioenergy crop but also highlights how simple yet deliberate design improvements, such as the use of inert gas and integrated heat recovery, can significantly enhance process efficiency. One of the most valuable aspects of this research is its emphasis on real-world applicability. By simulating a plant scaled for 1000 tonnes per year and grounding the design in local resource availability, the project shifts the conversation from lab-scale success to regional viability. The economic model suggests that, even at a modest production capacity, the system can become profitable within five to seven years, especially when the sale of co-products like biochar and the reuse of syngas for internal energy are factored in. These outcomes mirror earlier conclusions by Mohammed *et al*. (2015a) and Braga *et al*. (2014), who identified Napier grass as both abundant and underutilized in Africa's rural biomass economy. The catalytic upgrading of bio-oil was another critical success. Reducing acidity and oxygen content significantly improved the oil's storage and combustion characteristics, making it a better candidate for diesel replacement or blending. This quality enhancement, paired with a heating value close to 27 megajoules per kilogram, expands the potential uses of the oil in rural applications, from electricity generation to agricultural mechanization. As with many renewable fuels, achieving consistency and reliability in the product is key to gaining user confidence and market traction, and this study contributes meaningfully to that effort.

Beyond the technical data, the broader implications of adopting Elephant Grass pyrolysis are just as compelling. Environmentally, the system can operate with minimal carbon debt, as the feedstock itself is renewable and the by-products contribute to carbon capture or offset through soil enhancement and fuel displacement. Socially, the technology can be embedded within rural economies to generate employment, reduce fuel import dependency, and strengthen local energy autonomy. As noted by Okaraonye and Ikewuchi (2009), the ease of cultivating Elephant Grass without competing with food crops makes it a desirable option for sustainable rural development. To move this work forward, several steps are recommended. First, pilot-scale demonstrations in local communities are necessary to validate the system under real environmental and operational conditions. Such pilots will offer valuable insights into logistics, training needs, and maintenance cycles. Second, more detailed life-cycle assessments should be conducted to quantify the environmental benefits and guide policymakers in setting standards for bio-oil quality and emissions. Third, financial models should be refined to incorporate local pricing dynamics, subsidies, and carbon credit potential. These economic tools will help attract investment and encourage adoption by both public and private actors. Ultimately, further research is necessary to deepen our understanding of catalyst performance, oil upgrading pathways, and potential integration with other renewable technologies, such as solar drying or biogas recovery. Interdisciplinary collaboration among engineers, agronomists, economists, and local stakeholders will be essential in turning this opportunity into a scalable solution. The pyrolysis of Elephant Grass offers more than just a technical fix to energy shortages; it represents a pathway toward sustainable energy that is rooted in local ecosystems and economies. With thoughtful design, community engagement, and supportive policy, this approach could become a cornerstone of Africa's transition to cleaner, more inclusive energy systems.

Future Research

While this study has demonstrated the technical and economic viability of producing bio-oil from Elephant Grass through fast pyrolysis, it has also highlighted several areas where further research is not only desirable but essential. The complexity of biomass conversion technologies, combined with the variability of feedstock characteristics and local operating conditions, means that continued investigation is needed to refine and expand the scope of this work. One promising avenue lies in the deeper exploration of catalyst development for bio-oil upgrading. While zeolite cracking showed clear benefits in improving oil quality and stability, more research is needed into alternative catalysts that are low-cost, regionally available, and regenerable over multiple cycles. Tailoring catalysts to the specific composition of Elephant Grass-derived vapors could lead to even better fuel yields and more targeted removal of undesirable oxygenates. There is also value in comparing catalytic cracking with other upgrading methods such as hydrodeoxygenation, which could produce even cleaner fuels if the hydrogen supply chain can be integrated cost-effectively.

Another important area involves scaling the process beyond the demonstration or pilot level. While this study simulated a 1000-tonne-per-year system, the transition to full commercialization will require field validation under real-world environmental and logistical constraints. Future research should therefore focus on the design, testing, and optimization of modular systems that can be deployed in rural communities. These systems should be designed with minimal reliance on complex infrastructure and should prioritize ease of maintenance, local manufacturing, and operator training. Long-term field trials will also help assess the durability of reactor components, the variability of feedstock supply, and the seasonal impacts on system efficiency. In parallel with technical refinement, it will be crucial to perform a detailed life-cycle assessment of the process. While the carbon neutrality of the system is assumed based on the renewable nature of Elephant Grass, a formal evaluation of greenhouse gas emissions across the entire value chain, cultivation, harvesting, drying, conversion, and fuel use, will provide the necessary data to support informed policy decisions. Similarly, environmental impact assessments should evaluate water use, land use change, and any potential effects of large-scale grass cultivation on biodiversity.

Socioeconomic studies will also play a critical role in future research. Understanding how this technology integrates into the livelihoods of rural farmers, energy users, and small-scale entrepreneurs is essential for broad adoption. Future research should investigate business models that promote shared ownership, community-based management, and micro-financing for plant construction and operation. These models can help ensure that the benefits of biofuel production are distributed equitably and that local knowledge is incorporated into system design and operation. Finally, there is strong potential for integrating Elephant Grass pyrolysis with other renewable energy technologies to create hybrid systems that improve overall energy resilience. For example, coupling solar-powered drying units with the pyrolysis plant could reduce pre-processing energy demand, especially in regions with high solar irradiance. Additionally, the use of biochar in anaerobic digestion or as a substrate for microbial fuel cells could add new dimensions to energy recovery and waste valorization. Exploring these relationships could lead to the development of small-scale bio-refineries that deliver multiple forms of energy, soil enhancers, and bio-based products from a single feedstock. In essence, the work presented here lays a solid foundation, but it is only the beginning of what could be a transformative energy solution for developing regions. Future multidisciplinary, community-focused, and environmentally grounded research will be key to turning this potential into a long-term, sustainable impact.

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