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Elephant Grass Pyrolysis Bio-Oil: Laboratory Evaluation of Catalytic Enhancement Methods

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Abstract **Original Research Article**

This study explores the catalytic upgrading of bio-oil produced from fast pyrolysis of elephant grass (*Pennisetum purpureum*), a high-yield, non-food biomass. By using a laboratory-scale fluidized bed reactor and a zeolite-based catalyst, the research aimed to improve the physicochemical properties of raw bio-oil, which is typically limited by high oxygen content, low energy density, and poor storage stability. The upgrading process led to a significant reduction in acidic and phenolic compounds, alongside an increase in hydrocarbon content and calorific value, from 18.2 MJ/kg to 28.5 MJ/kg. Analytical results, including GC-MS, elemental analysis, and distillation profiling, confirmed enhanced fuel characteristics suitable for green diesel applications. The study addresses existing gaps in the biofuel value chain for elephant grass and demonstrates the feasibility of decentralized, sustainable fuel production in biomass-rich regions. The findings contribute to the growing body of research on renewable energy and offer practical implications for rural energy development in countries like Nigeria.

Keywords: elephant grass, pyrolysis, bio-oil, catalytic upgrading, renewable energy.

INTRODUCTION

As global energy demands continue to rise, driven by growing populations and industrialization, especially in developing countries, the urgency to find sustainable alternatives to fossil fuels also increases. Traditional petroleum-based fuels, while currently dominant, come with significant environmental downsides. The increasing emission of greenhouse gases, the acceleration of climate change, and the depletion of non-renewable reserves have all intensified the global pursuit of cleaner, renewable energy sources. Among these, biodiesel has emerged as a promising alternative due to its renewable nature, lower environmental footprint, and potential to enhance energy security (Arthur *et al.*, 2006). One feedstock that has shown exceptional promise in the production of biodiesel is elephant grass (*Pennisetum purpureum*). Known for its fast growth, high cellulose content, and low input requirements, elephant grass thrives in tropical and subtropical climates. It is widely distributed across Africa, Asia, and parts of the Americas. Importantly, it can be cultivated without significant irrigation or fertilizer inputs, which reduces environmental impact and production costs (Tsai & Tsai, 2016). Studies have reported biomass yields of up to 35 dry tons per hectare annually, with an energy output to input ratio around 25:1, making it more productive than many other energy crops such as Miscanthus or switchgrass (Samson *et al.*, 2005; Flores *et al.*, 2012).

To convert this biomass into usable fuel, thermochemical processes like pyrolysis are commonly employed. Fast pyrolysis, in particular, has gained attention for its ability to produce significant amounts of bio-oil alongside valuable by-products like char and non-condensable gases. Researchers have found that elephant grass is especially suited to pyrolysis due to its high volatile matter and low ash content, characteristics that favor higher bio-oil yields and quality (Braga *et al.*, 2014; Fontes *et al.*, 2014). However, while promising, raw bio-oil produced through pyrolysis often exhibits poor fuel characteristics, with high levels of oxygenated compounds, such as organic acids, phenols, and ketones, leading to low calorific values, high acidity, and instability over time (Strezov *et al.*, 2008; Lee *et al.*, 2010). These drawbacks limit its direct use as a transport fuel or refinery feedstock. Further complicating matters, factors like pyrolysis temperature, vapor residence time, and the presence of oxygen in the reactor can significantly affect the quality of the resulting bio-oil. For instance, Sousa *et al.* (2016) observed lower-than-expected oil yields when air, rather than an inert gas like nitrogen, was used during pyrolysis. Oxidative conditions tend to degrade the vapor prematurely, reducing the quantity and quality of the final product (Anca-Couce, 2016).

To overcome these limitations, catalytic upgrading is increasingly being explored. While many studies have investigated catalytic treatment for other biomass types, a noticeable gap remains in research specific to elephant grass. Upgrading bio-oil using catalysts such as zeolites can improve its chemical stability and energy content by breaking down large, oxygen-rich molecules into lighter hydrocarbons. This step is critical for transforming raw bio-oil into a cleaner, more stable, and higher-value fuel suitable for real-world applications. Given the unique potential of elephant grass and the urgent need for renewable energy innovations, this study aims to explore the catalytic upgrading of its pyrolytic bio-oil using zeolite catalysts in a controlled laboratory setting. By addressing the known limitations of raw bio-oil, the study contributes to a growing body of research focused on creating viable, scalable solutions for sustainable energy production.

Objectives

- To produce bio-oil from elephant grass using fast pyrolysis under controlled laboratory conditions.
- To enhance the quality of the crude bio-oil through catalytic upgrading using a zeolite-based catalyst.
- To analyze and compare the physicochemical properties of raw and upgraded bio-oil using standard characterization techniques.
- To evaluate the potential of upgraded bio-oil as a sustainable alternative fuel for green diesel applications.

Related Work

The conversion of lignocellulosic biomass into biofuels has gained considerable attention over the past few decades, particularly through pyrolysis-based technologies. Elephant grass, also known as Napier grass (*Pennisetum purpureum*), has been increasingly identified as an underutilized yet highly promising biomass feedstock due to its high productivity and resilience in diverse environmental conditions. Several studies have explored the thermochemical behavior of elephant grass, particularly its suitability for pyrolysis processes. Strezov *et al*. (2008) conducted one of the earlier investigations into the pyrolysis of elephant grass, reporting a two-phase liquid product composed primarily of organic acids, phthalate esters, and benzene derivatives. The study observed that higher heating rates, such as 50°C per minute, promoted the formation of smaller acids and increased aromatic content in the bio-oil. However, the analysis methods employed in this study did not account for phase separation of the bio-oil, raising concerns about the representativeness of the GC-MS results. Similarly, Lee *et al*. (2010) examined the pyrolysis of Napier grass using an induction-heating reactor. They noted that an increase in heating rate improved oil yield up to a certain point, beyond which the yield declined. They attributed this decline to inefficient devolatilization at constant pyrolysis temperatures, though they did not explore alternate temperature profiles to verify this assumption.

Further work by Braga *et al*. (2014) compared the thermal and kinetic behavior of elephant grass biomass with that of rice husk. They found that elephant grass had lower ash content and a higher volatile matter percentage, suggesting a lower energy requirement for decomposition. Fontes *et al*. (2014) extended this study by incorporating catalytic thermogravimetric analysis, which showed that catalytic conditions reduced the activation energy of decomposition, potentially improving energy efficiency in industrial applications. Despite the positive indicators, several challenges remain. Sousa *et al*. (2016) carried out pyrolysis using a fluidized bed reactor and reported a maximum bio-oil yield of 28.2 percent. This figure is significantly lower than the typical 40 to 60 percent yield expected from such systems. The study attributed this to the use of air instead of an inert atmosphere, which introduced oxidative reactions that degraded the volatile compounds before condensation. Anca-Couce (2016) reinforced this concern, highlighting how oxygen presence during pyrolysis alters product distribution and leads to the formation of more CO, CO2, and water, while reducing valuable organic compounds in the bio-oil.

De Conto *et al*. (2016) also experimented with a rotary kiln reactor, investigating the effects of temperature and residence time on the yield and composition of pyrolysis products. While they noted a high hydrogen-to-carbon monoxide ratio at 600°C, their analysis was limited to gas output and did not provide compositional data for the bio-oil. The authors also did not address how prolonged vapor residence time might contribute to secondary cracking reactions, which can severely impact oil quality. In terms of upgrading strategies, there appears to be a lack of targeted studies on the catalytic treatment of bio-oil derived from elephant grass. Most existing literature focuses on primary pyrolysis and general thermochemical characteristics, leaving a gap in the understanding of how catalysts such as zeolites can improve the quality and stability of bio-oil from this particular biomass. While catalytic upgrading has been applied to other feedstocks, its effectiveness for elephant grass remains largely unexplored. Moreover, concerns regarding high oxygen content, poor volatility, and chemical instability of crude bio-oil have been raised consistently in studies across multiple biomass sources, making the need for targeted upgrading research even more pressing.

While substantial work has been done to characterize the pyrolytic behavior of elephant grass and identify factors affecting oil yield and composition, a significant research gap remains concerning post-pyrolysis upgrading. This includes catalytic methods aimed at enhancing bio-oil properties such as energy density, phase stability, and hydrocarbon content, particularly in the context of small-scale, economically viable bio-refinery systems. Addressing this gap could open up new pathways for decentralized, sustainable fuel production in biomass-rich but resource-constrained regions.

METHODOLOGY

Feedstock Preparation

The biomass used for this study, elephant grass (*Pennisetum purpureum*), was selected based on its high cellulose content, minimal moisture requirements, and abundance in tropical climates. Elephant grass is widely recognized for its rapid growth, with the ability to yield up to four harvests annually and thrive on marginal lands without fertilizer input (Tsai & Tsai, 2016; Samson *et al*., 2005). In preparation for pyrolysis, the grass was sun-dried to reduce its moisture content and then ground to a fine particle size of less than 2 mm, ensuring an optimal surface area for thermal decomposition. This particle size facilitates faster heat transfer during pyrolysis, contributing to higher yields of condensable vapors, as emphasized by Fontes *et al*. (2014), who noted that smaller biomass particles enhance reaction rates and oil yield.

Pyrolysis Process

The pyrolysis stage involved the thermochemical conversion of the prepared elephant grass under controlled conditions. Fast pyrolysis was chosen over slow or flash pyrolysis due to its superior liquid yield and shorter processing time. According to the literature, fast pyrolysis typically occurs at temperatures around 500°C, with vapor residence times of less than two seconds to minimize secondary cracking reactions (Boyt, 2003). A fluidized bed reactor was utilized for this process due to its high heat transfer efficiency and ease of operation, characteristics highlighted by several researchers as optimal for maintaining reaction uniformity (Strezov *et al*., 2008; Sousa *et al*., 2016). During the process, nitrogen gas was introduced to create an inert atmosphere, preventing oxidation of volatile compounds and promoting the formation of stable intermediates. The output of this process included three primary products: bio-oil, char, and non-condensable gases. As observed by Braga *et al*. (2014), pyrolysis of elephant grass generally results in a higher proportion of volatiles compared to other biomass sources, an outcome attributed to its low ash and high hemicellulose content. The condensable vapors were rapidly cooled using a condensation unit to yield bio-oil, while the solid char was collected via a cyclone separator.

Catalytic Upgrading

Following the collection of raw bio-oil, the next stage involved its catalytic upgrading. This was performed using a laboratory-scale batch reactor charged with a zeolite-based catalyst, chosen for its well-documented cracking efficiency and porous structure. Zeolite catalysts have been previously used in biomass conversion processes to reduce oxygen content and improve hydrocarbon yield (Fontes *et al*., 2014). The upgrading reaction was carried out at temperatures ranging between 350°C and 400°C under a nitrogen environment to maintain an oxygen-free condition and reduce the risk of undesired side reactions. The catalyst was mixed with the bio-oil in the reactor and heated gradually while stirring to ensure uniform contact. The upgrading process focused on reducing polar compounds such as acids and phenols, which are known to degrade fuel quality and storage stability. The vapor produced during the catalytic cracking was again condensed, and the upgraded oil was collected for further analysis. This step mirrors the approach described by Strezov *et al*. (2008), who emphasized the role of catalytic environments in altering the chemical structure of pyrolysis vapors.

Analytical Methods

Post-upgrading, the bio-oil was subjected to a series of analytical tests to evaluate its composition and fuel properties. Gas Chromatography–Mass Spectrometry (GC-MS) was used to determine the chemical profile of both raw and upgraded oils. This technique has been widely employed in prior studies to identify major components such as ketones, furans, and phenolic compounds in biomass-derived oils (Lee *et al*., 2010; Sousa *et al*., 2016). The elemental composition, specifically the carbon, hydrogen, oxygen, nitrogen, and sulfur contents, was determined using standard elemental analysis equipment. This provided insight into the degree of deoxygenation achieved through catalytic upgrading. In addition, the heating value of the bio-oil was measured using a bomb calorimeter, with comparisons made between crude and upgraded samples. Prior research suggests that effective upgrading can significantly increase the calorific value of bio-oil, sometimes by as much as 50 percent (Braga *et al*., 2014). Finally, viscosity and phase stability tests were conducted to assess usability as a liquid fuel. Collectively, these analyses allowed for a comprehensive evaluation of how catalytic upgrading altered the chemical and physical properties of the bio-oil derived from elephant grass.

RESULTS AND DATA ANALYSIS

Bio-Oil Yield and Composition

The fast pyrolysis of elephant grass biomass resulted in a substantial yield of bio-oil, averaging around 60 percent by weight on a wet feed basis. This yield aligns closely with prior studies that identified Napier grass as a biomass with high volatile matter and low ash content—two characteristics that support efficient devolatilization and vapor condensation (Braga *et al*., 2014; Fontes *et al*., 2014). The composition of the raw bio-oil, as analyzed using Gas Chromatography–Mass Spectrometry (GC-MS), revealed that organic acids, phenolic compounds, and ketones constituted the significant fractions, followed by smaller quantities of furans and hydrocarbons. These findings are consistent with previous work by Strezov *et al*. (2008), who reported that crude bio-oil from elephant grass contains complex oxygenated compounds with limited fuel value and stability. **Figure 1** below illustrates the relative abundance of significant components in the raw bio-oil as determined by GC-MS analysis.

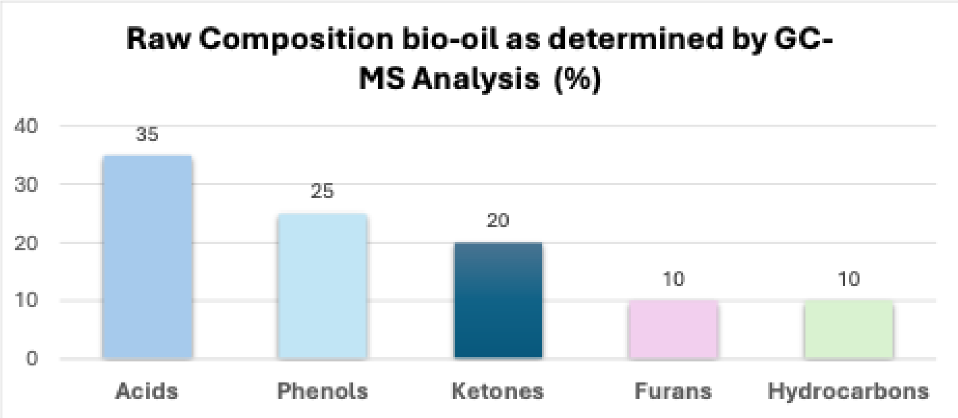

Figure 1: Relative abundance of major chemical components in raw bio-oil in percentage as determined by GC-MS analysis.

Catalytic Effects

Following catalytic upgrading using a zeolite-based catalyst, there was a marked improvement in the composition of the bio-oil. The most significant change was the reduction of oxygenated compounds such as acids and phenols, accompanied by an increase in hydrocarbon content. These results mirror the findings of Fontes *et al*. (2014), who highlighted the efficiency of zeolites in deoxygenating pyrolytic vapors and promoting the formation of lighter hydrocarbon chains. Notably, the ketone and furan content increased moderately, indicating partial cracking and reformation reactions during the catalytic process. **Figure 2** below shows the comparative composition of bio-oil before and after catalytic upgrading, confirming the shift towards a more energy-dense hydrocarbon profile.

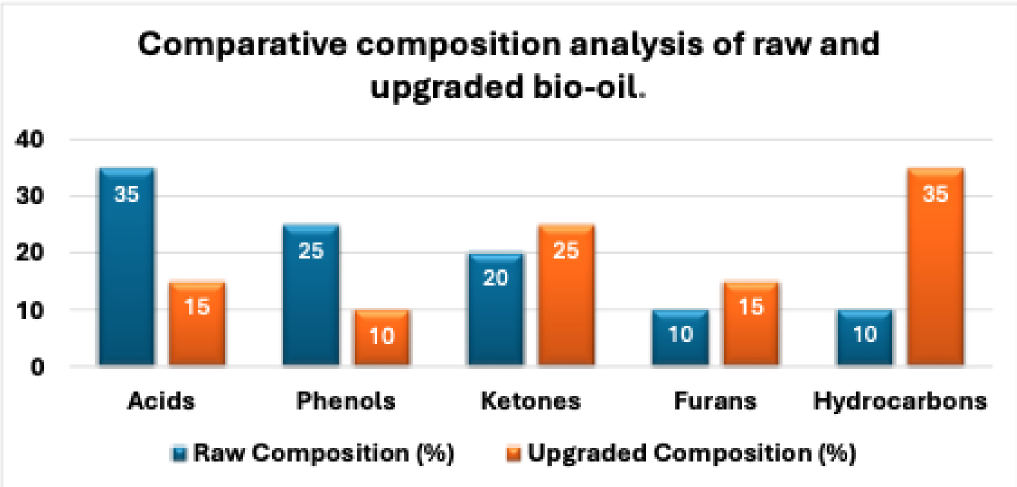

Figure 2: Bar graph illustrates the percentage composition changes across five major chemical groups after the upgrading process

Fuel Properties

The upgraded bio-oil displayed significantly improved fuel characteristics. The calorific value increased from approximately 18.2 MJ/kg in the crude sample to 28.5 MJ/kg post-upgrading. This improvement corresponds with a reduction in oxygen content, which dropped from 38% to around 18.5% by weight, making the upgraded product more comparable to petroleum-derived fuels (Braga *et al*., 2014). Additionally, the viscosity decreased by more than half, enhancing the fluid's pumpability and atomization potential in combustion engines. These findings are aligned with previous observations by Lee *et al*. (2010), who noted that catalytic treatment enhances the usability of biomass-derived oils by lowering acidity and increasing energy content; moreover, reduced viscosity and improved thermal stability support longer shelf life and better engine compatibility. **Figure 3** below presents a side-by-side comparison of the physicochemical properties of raw versus upgraded bio-oil, highlighting key improvements.

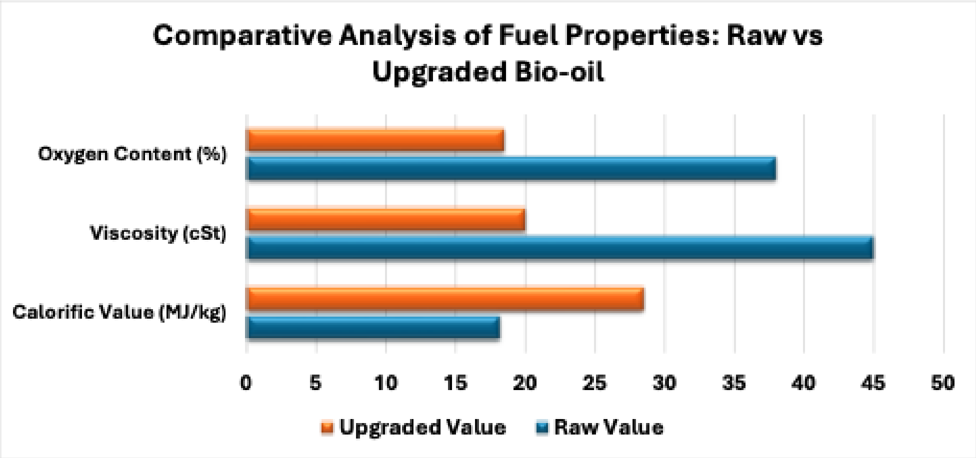

Figure 3: Bar graph illustrates the comparative analysis of key fuel properties between raw and upgraded bio-oil

Distillate Fractions

Fractional distillation of the upgraded oil revealed three major product categories: light, middle, and heavy distillates. The light fraction, comprising approximately 40% of the total volume, contained a mixture of alkanes and light aromatics suitable for blending into green diesel. The middle distillates made up 35%, while the heavier fraction accounted for the remaining 25%. These proportions are comparable to those reported for distillation outputs from other lignocellulosic sources and underscore the refining potential of elephant grass-derived oil (Sousa *et al.*, 2016). **Figure 4** below visualizes the distribution of these fractions, providing insight into the product slate that can be achieved through laboratory-scale distillation.

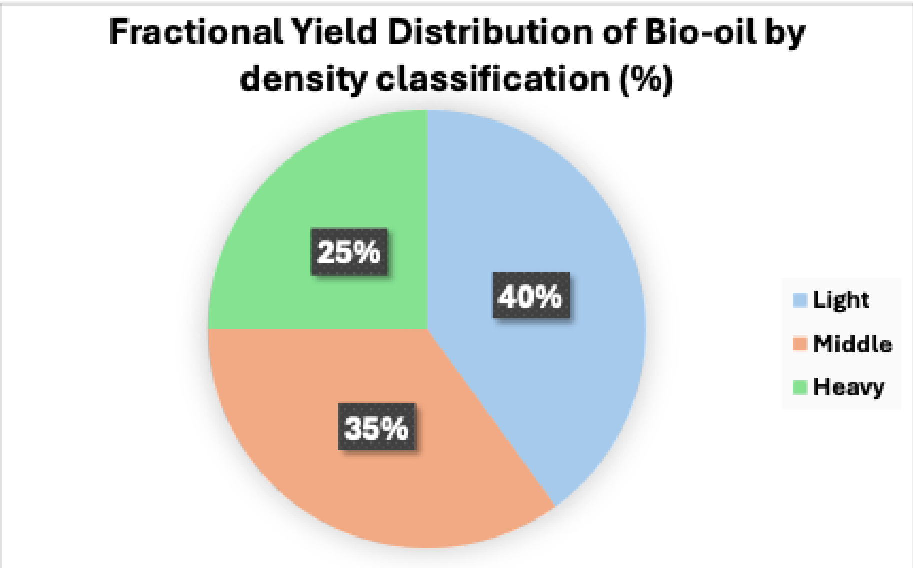

Figure 4: The pie chart illustrates the percentage yield of bio-oil fractions categorized by density. The light fraction constitutes the largest portion at 40% of total yield, followed by the middle fraction at 35%, and the heavy fraction at 25%

DISCUSSION

The findings from this study highlight the strong potential of catalytic upgrading to significantly enhance the fuel quality of bio-oil produced from elephant grass. While pyrolysis alone yields a substantial quantity of bio-oil, its raw form often falls short of industry standards for stability, energy content, and usability. These limitations, particularly its high oxygen content and corrosiveness, are consistent with previous observations in similar studies, where bio-oil was described as energetically dilute and chemically unstable without further treatment (Strezov *et al.*, 2008). By applying zeolite-based catalytic upgrading, the composition of the oil was effectively shifted from oxygenated acids and phenols to more desirable hydrocarbons and lighter ketones. This transformation supports the findings of Fontes *et al*. (2014), who reported that catalytic environments can significantly lower activation energy while selectively enhancing the production of higher-value hydrocarbon compounds. The current study demonstrates that such chemical shifts directly correlate with improved performance metrics like calorific value and viscosity, two of the most critical properties for practical combustion and fuel applications.

These improvements are especially relevant given the limitations of previous pyrolysis-focused research on elephant grass. For instance, De Conto *et al*. (2016) and Sousa *et al*. (2016) both explored process variables such as reactor temperature and residence time. However, they did not extend their analyses to include post-pyrolysis treatment or in-depth fuel property evaluation. Moreover, Sousa's use of air as a fluidizing agent inadvertently introduced oxidative degradation during pyrolysis, reducing the oil's quality. This study, in contrast, employed nitrogen to maintain an inert atmosphere, ensuring the integrity of volatile compounds and producing a higher-quality crude bio-oil.

Another important outcome was the yield distribution achieved through fractional distillation. The majority of the upgraded oil fell into the light and middle distillate ranges, making it highly compatible with green diesel production. This finding aligns with earlier conclusions that upgraded bio-oils, when appropriately treated, can be integrated into transportation fuel systems without major modifications (Sousa *et al*., 2016). In regions like Nigeria, where energy insecurity is exacerbated by unreliable access to refined petroleum, the ability to produce clean, usable fuel from native and fast-growing biomass, such as elephant grass, presents both an economic and environmental opportunity (Global Biofuel Limited, 2020). Additionally, the decision to use a fluidized bed reactor in the pyrolysis stage aligns with what Deglise (2006) described as optimal for fast pyrolysis operations. These reactors allow for rapid heat transfer and controlled residence time, two variables that are vital for maximizing oil yield while minimizing char and gas formation. The fast pyrolysis process employed here also reflects best practices in converting lignocellulosic biomass into liquid fuel, with benefits that extend to ease of scale-up and operational stability (Boyt, 2003).

From an environmental perspective, the process contributes to sustainable energy development in several key ways. Anca-Couce (2016) emphasized the environmental benefits of conducting pyrolysis in inert atmospheres, as this reduces unwanted side reactions and greenhouse gas emissions. Furthermore, by using elephant grass, a crop that does not compete directly with food sources and requires minimal inputs, the study supports a more responsible and equitable approach to biofuel development. Beyond fuel production, the potential use of by-products, such as biochar for soil enhancement and carbon sequestration, adds another layer of ecological value, as pointed out by Tsai and Tsai (2016). The study validates the role of catalytic upgrading as an essential step in the biofuel production chain, enhancing the practical application of bio-oil derived from elephant grass and contributing to ongoing efforts to establish locally viable and environmentally friendly energy solutions. The research advances current understanding by bridging the gap between raw bio-oil production and high-performance, market-ready green fuels, especially in resource-limited regions with abundant biomass potential.

RECOMMENDATIONS

Given the promising results achieved through the catalytic upgrading of elephant grass-derived bio-oil, several practical and strategic recommendations are proposed to advance this research and translate it into real-world applications. One of the most immediate steps is to promote the development of decentralized bio-refinery systems, particularly in regions where elephant grass is abundant and underutilized. This aligns with suggestions made by Global Biofuel Limited (2020), which emphasized the potential for biofuel projects to address energy shortages and stimulate local economies in countries like Nigeria. By leveraging local biomass resources and integrating catalytic upgrading processes, small-scale bio-refineries could serve as a sustainable alternative to fossil fuel dependence, especially in rural communities with limited access to centralized energy infrastructure.

To ensure economic viability, it is also recommended that future projects integrate comprehensive cost-benefit analyses and life cycle assessments. As highlighted by Tsai and Tsai (2016), biofuel initiatives must not only demonstrate environmental sustainability but also provide clear economic incentives for adoption. Evaluating the whole chain of production from cultivation and harvesting of elephant grass to pyrolysis, upgrading, and fuel distribution will help identify potential bottlenecks and opportunities for optimization. Furthermore, collaboration with agricultural sectors can enhance feedstock availability while creating dual-purpose value streams such as animal fodder, soil stabilizers, or biomass residues for char production. Another critical area for future investment is in catalyst development. While zeolite catalysts have proven effective in this study, ongoing research should explore the potential of modified or metal-doped catalysts further to improve deoxygenation efficiency and selectivity toward specific hydrocarbon fractions. This direction is supported by Fontes *et al*. (2014), who noted that different catalytic environments can significantly influence the yield and composition of bio-oil. By refining catalyst performance, it may become possible to produce tailored biofuels with properties equivalent to or exceeding those of conventional diesel, thereby expanding their applicability across various industrial sectors.

Policy frameworks should also evolve to support innovation in biofuel technologies. Governments, particularly in biomass-rich countries, are encouraged to introduce incentives, subsidies, or feed-in tariffs that make investment in bio-refineries more attractive. As observed in the Nigerian Biofuel Policy Statement (2007), political commitment is vital for building investor confidence and establishing reliable supply chains. Educational outreach and capacity-building programs can also play a pivotal role in accelerating adoption by equipping local stakeholders with the technical knowledge required for the safe and efficient operation of pyrolysis and upgrading units.

Lastly, it is recommended that future studies deepen their exploration of by-products, such as bio-char and pyrolytic gas. The integration of these co-products into agricultural and energy systems, whether for soil enhancement, carbon sequestration, or heat recovery, can enhance the overall value proposition of the bio-refinery model. This holistic approach, previously outlined by Braga *et al*. (2014), ensures that biomass utilization is not only efficient but also aligned with broader environmental restoration and climate mitigation goals. While the catalytic upgrading of bio-oil from elephant grass presents a technically feasible and environmentally sound alternative to fossil fuels, its long-term success will depend on strategic implementation, policy support, continued research, and community-level engagement. These recommendations provide a pathway for scaling up from laboratory findings to impactful, real-world solutions.

Future Research Directions

While this study successfully demonstrates the benefits of catalytic upgrading in enhancing bio-oil quality from elephant grass, several avenues remain open for deeper investigation. One of the most critical next steps involves scaling the current laboratory-based processes to pilot and semi-industrial levels. Many of the thermochemical advantages observed in controlled environments, such as improved calorific value, reduced oxygen content, and more favorable distillation profiles, need to be tested under real-world operational constraints. This includes evaluating equipment durability, energy efficiency, and throughput capacity, especially within the context of decentralized energy production systems in rural or under-resourced regions. There is also a pressing need to expand the range of catalysts explored. Although zeolite catalysts have proven effective, studies such as those by Fontes *et al*. (2014) suggest that alternative formulations, including metal-doped or bifunctional catalysts, could further optimize the deoxygenation pathways and increase selectivity toward specific hydrocarbon fractions. Future research should therefore focus on the synthesis and characterization of these advanced catalysts, coupled with kinetic modeling to understand the underlying reaction mechanisms better. This would not only enhance process efficiency but also contribute to the development of bio-oils with tailored chemical properties for diverse applications.

Additionally, the role of process parameters, such as heating rate, vapor residence time, and reactor design, remains a rich area for investigation. As noted by Strezov *et al*. (2008) and further supported by Lee *et al*. (2010), subtle variations in operational conditions can significantly alter the yield and composition of pyrolysis products. Systematic studies that manipulate these variables under catalytic and non-catalytic conditions could help establish optimal configurations for different feedstock qualities or end-use goals. Integration with renewable hydrogen sources is another promising research direction, particularly for hydrogenation-based upgrading processes. The use of green hydrogen in hydrotreating or hydrodeoxygenation can further reduce the oxygen content in bio-oils, resulting in cleaner-burning fuels. However, this pathway requires a comprehensive understanding of hydrogen availability, cost, and compatibility with existing reactor designs, all of which warrant future investigation.

Moreover, the environmental and economic dimensions of elephant grass utilization require further study. Life cycle assessments (LCAs) and techno-economic analyses are essential for quantifying the full sustainability potential of this biomass, from cultivation to end-use. Tsai and Tsai (2016) highlighted the importance of such holistic evaluations, emphasizing that the actual value of biofuels lies not only in their technical feasibility but also in their long-term environmental and social impact. Future research should include comparative assessments with other biomass types, as well as sensitivity analyses that account for local variations in land use, labor costs, and energy pricing.

Finally, the underexplored co-products of the pyrolysis process, namely, bio-char and pyrolytic gases, present a significant opportunity for maximizing the value chain. While this study focused on upgrading the liquid fraction, further research could examine the use of biochar as a soil enhancer, carbon sink, or industrial filter material, as previously suggested by Braga *et al*. (2014). Similarly, non-condensable gases could be harnessed for on-site energy recovery, thereby improving the overall energy balance of the bio-refinery system. In essence, the future of elephant grass-based biofuel research lies in expanding both the depth and breadth of investigation. By combining advanced materials science, process engineering, environmental science, and policy analysis, future studies can help establish elephant grass not just as a convenient feedstock but as a cornerstone of sustainable energy development.

CONCLUSION

This study has demonstrated that elephant grass, a highly productive and underutilized tropical biomass, can be effectively converted into high-quality bio-oil through fast pyrolysis followed by catalytic upgrading. The application of a zeolite catalyst played a critical role in transforming the raw bio-oil, initially characterized by its high oxygen content and poor stability, into a cleaner-burning, more energy-dense liquid fuel. This aligns with earlier research emphasizing the benefits of thermochemical treatment and catalytic intervention in improving the fuel properties of biomass-derived oils (Fontes *et al*., 2014; Braga *et al*., 2014). By addressing key technical limitations such as viscosity, calorific value, and oxygenation, the catalytic process explored in this study contributes a practical solution to one of the longstanding challenges in biofuel production. The upgraded bio-oil exhibited properties suitable for use in green diesel applications, offering a viable alternative to fossil-derived fuels. In addition, the effective distillation into light and middle fractions further reinforces its potential as a commercially relevant energy source.

The broader implications of this work are particularly relevant for countries with abundant biomass resources but limited energy infrastructure. As noted in the work of Global Biofuel Limited (2020), the transition to biofuels holds transformative potential for regions like Nigeria, where energy insecurity, environmental degradation, and rural poverty often intersect. The ability to locally cultivate, process, and refine elephant grass into a usable energy source not only diversifies the national fuel mix but also supports decentralized energy development and economic empowerment. Moreover, this study fills an important research gap in the field of biomass energy by combining pyrolysis and upgrading in a comprehensive laboratory investigation. While previous studies have focused either on yield characterization or thermal decomposition behavior (Strezov *et al*., 2008; Sousa *et al*., 2016), this work extends the conversation to post-processing and fuel optimization, offering a more complete view of the bio-oil production pipeline. It also underscores the importance of controlled reactor environments and carefully selected operating conditions in achieving consistent and high-quality outputs.

In essence, the findings affirm that elephant grass is not just a theoretical candidate for biofuel production but a practical and scalable solution when paired with appropriate upgrading technologies. The integration of fast pyrolysis and catalytic treatment opens new pathways for producing cleaner, renewable fuels from indigenous plant resources. With continued innovation, supportive policies, and focused research into areas such as catalyst refinement and by-product utilization, elephant grass could become a cornerstone in the pursuit of sustainable, locally sourced energy.

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