ENERGY SYSTEMS
&
APPLICATIONS

https://esajournal.com

Research paper

Optimization and Fuel Property Characterization of Bio-Oil From Catalytic Pyrolysis of Achyranthes Aspera Wood Residue Using Zeolite Y Catalyst

Joseph A. Oyebanji[a], *Kifilideen L. Osanyinpeju*[b,*], *Adejoke C. Adetunji*[a], *Ife A. Adetokunbo*[a], *Olukunle O. Olalekan*[a]

[a]Department of Mechanical Engineering, College of Engineering (COLENG), Bells University of Technology, Ota, Ogun State, Nigeria.
[b]Department of Agricultural and Bio-Systems Engineering, College of Engineering (COLENG), Bells University of Technology, Ota, Ogun State, Nigeria.
[*]**Corresponding author:** kosanyinpeju@bellsuniversity.edu.ng

Article information:
Received: 25/12/2025, Revision: 27/03/2026, Accepted: 28/03/2026.
DOI: https://doi.org/10.5281/zenodo.20938597

ABSTRACT

The growing demand for renewable alternatives to fossil fuels has intensified interest in biomass pyrolysis for bio-oil production. Despite the wide availability of *Achyranthes aspera* wood residue as an underutilised tropical lignocellulosic biomass, its pyrolytic bio-oil properties remain entirely unreported, limiting evaluation of its renewable fuel potential. This study investigated bio-oil yield distribution and physicochemical fuel properties from catalytic pyrolysis of *Achyranthes aspera* wood residue in a fixed-bed reactor at 400 °C and 500 °C, using four biomass-to-zeolite Y catalyst ratios (100/0, 95/5, 90/10, and 85/15 weight percent (wt.%)). Product yields were quantified by mass balance and analysed using descriptive statistics and two-way ANOVA. Bio-oil yield was optimised via a desirability function, maximising liquid yield (weight = 0.5) while minimising biochar and syngas (weight = 0.25 each). Fuel properties: flash point, pour point, pH, density, kinematic viscosity, American Petroleum Institute (API) gravity, and higher heating value (HHV) were determined per ASTM standards (D445, D4052, D93, D97, D2500, D7946-19), with HHV estimated from elemental analysis correlations. Desirability optimisation identified 95/5 at 500 °C as optimal, achieving a score of 88.77, with 52.95 wt.% bio-oil, 22.00 wt.% biochar, and 25.05 wt.% syngas. ANOVA indicated that temperature significantly affected biochar yield ($p < 0.05$) and catalyst ratio significantly influenced syngas yield ($p < 0.05$), noting that these results are based on a single observation per treatment combination using the interaction term as a proxy error term. Flash points of 76–82 °C exceeded diesel (50 °C), indicating improved storage safety. Pour points of −3 to −4 °C confirmed adequate low-temperature flow. pH rose from 7.50 (non-catalytic) to 8.50 (85/15 ratio), demonstrating deoxygenation and reduced corrosion risk relative to typical bio-oil pH of 2.0–3.8. Densities (0.78–0.85 g/mL), viscosities (4.00–4.30 cSt), and API gravities (40.00–45.58) fell within petroleum fuel specifications. HHVs increased from 29.04–29.07 MJ/kg (non-catalytic) to 32.07–32.80 MJ/kg (catalytic), confirming energy density improvement with catalyst loading. Zeolite Y catalytic pyrolysis at 95/5 and 500 °C delivers near-diesel fuel properties, establishing *Achyranthes aspera* wood residue as a promising renewable feedstock for industrial energy applications.

Keywords: *Fuel properties, Physicochemical, Catalytic pyrolysis, Achyranthes aspera, Renewable energy, Bio-oil.*

Cite as: Oyebanji, J. A., Osanyinpeju, K. L., Adetunji, A. C., Adetokunbo, I. A., & Olalekan, O. O. (2026). Optimization and fuel property characterization of bio-oil from catalytic pyrolysis of achyranthes aspera wood residue using zeolite Y catalyst. Energy Systems & Applications, 1(1): 31-54.

I. INTRODUCTION

The extensive reliance on fossil fuels remains one of the primary contributors to greenhouse gas emissions, environmental degradation, and global warming, all of which disrupt the balance of natural ecosystems and accelerate climate change (Osanyinpeju et al., 2018a; Osanyinpeju et al., 2018b; Chukwuneke et al., 2022). To mitigate these adverse effects, renewable energy sources have gained increasing attention as sustainable, eco-friendly, and reliable alternatives capable of meeting global energy demands with minimal environmental impact (Osanyinpeju et al., 2018c; Osanyinpeju et al., 2018d; Nigam, 2023).

Among renewable energy technologies, biomass conversion stands out as a promising carbon-neutral approach for producing fuels and value-added chemicals (Chukwuneke, et al., 2020). Pyrolysis, a thermochemical conversion process that occurs under limited or no oxygen, has received considerable interest due to its ability to decompose lignocellulosic biomass into three major products: bio-oil, biochar, and syngas (Maulinda, et al., 2023). Among these, bio-oil is especially attractive because it is a liquid intermediate that can potentially substitute petroleum-based fuels. However, its direct application is limited due to undesirable properties such as high oxygen content, acidity, chemical instability, and low heating value, which collectively hinder storage stability, combustion performance, and compatibility with existing fuel systems (Hu and Gholizadeh, 2020; Ameh et al., 2024).

Comprehensive physicochemical and fuel property characterization is essential to evaluate the quality of bio-oil, identify its limitations, and determine the level of upgrading required for practical utilization (Stelmach et al., 2023). Key parameters; such as elemental composition, calorific value, moisture content, viscosity, and density; directly influence combustion efficiency, storage behavior, and blending compatibility with conventional petroleum fuels (Yusof et al., 2025; Adegoke et al., 2021). Without reliable data on these parameters, the transition of bio-oil from laboratory-scale research to industrial or commercial energy applications remains uncertain (Chiaberge et al., 2014; Kaoje et al., 2025)

Although several studies have examined bio-oils from different biomass sources, limited information exists regarding the physicochemical and fuel properties of bio-oil derived from *Achyranthes aspera* wood residue. This underutilized lignocellulosic biomass is abundant in many tropical regions but has not been thoroughly investigated for energy applications. Critical parameters; such as calorific value, viscosity, density, flash point, pour point, and pH; remain underreported, creating a knowledge gap that limits proper assessment of its renewable fuel potential and its comparability to other bio-oil feedstocks (Pinto et al., 2012; Kassem et al., 2018; Cai et al., 2020). Understanding these characteristics is crucial to determine its combustion behavior, storage stability, and environmental impact. Furthermore, valorizing *Achyranthes aspera* aligns with circular economy principles, enabling waste-to-energy conversion, environmental conservation through biomass utilization, and economic benefits from renewable fuel production (Santoso et al., 2022).

Despite the abundance of *Achyranthes aspera* wood residue in tropical regions, comprehensive data on its pyrolytic behavior and bio-oil properties remain unavailable. Specifically: fuel properties (HHV, viscosity, pH, density) are unreported, effect of zeolite Y catalyst on product distribution is unknown, optimal pyrolysis conditions have not been established, comparison with conventional fuels is absent.

This study makes several original contributions that distinguish it from existing literature on biomass pyrolysis and bio-oil characterization. While previous investigations have extensively examined bio-oil from commonly studied feedstocks such as Gmelina arborea (Adegoke et al., 2021), Switchgrass (Imam and Capareda, 2012), Spirulina platensis (Jamilatun et al., 2020), Tanjong leaves (Maulinda et al., 2023a), and various lignocellulosic biomasses including wheat straw, timothy grass, and pinewood (Nanda et al., 2014), no published study has yet reported the physicochemical and fuel properties of bio-oil derived from *Achyranthes aspera* wood residue. This represents a fundamental gap in the bio-oil literature, as *Achyranthes aspera* is a widely distributed yet entirely underexplored lignocellulosic residue in tropical regions, particularly in Nigeria and sub-Saharan Africa, where it accumulates as agricultural waste without any established energy valorization pathway.

Therefore, this study investigates the physicochemical and fuel properties of bio-oil produced from catalytic pyrolysis of *Achyranthes aspera* wood residue at 400 °C and 500 °C, using zeolite Y catalyst at varying biomass-to-catalyst ratios (100/0, 95/5, 90/10, and 85/15). The objective is to evaluate how temperature and catalyst loading influence bio-oil yield, fuel properties, and energy potential, thereby providing essential data to support the integration of *Achyranthes aspera* -based bio-oil into renewable fuel systems.

II. MATERIAL AND METHOD

This study investigated the production and characterization of bio-oil derived from the catalytic pyrolysis of *Achyranthes aspera* wood residue. The experimental procedure involved several stages, including feedstock collection and preparation, catalytic pyrolysis under controlled thermal conditions, and subsequent analysis of product yields and fuel properties. The *Achyranthes aspera* wood residue was sourced from Ota, Ogun State, Nigeria, milled, sieved to a particle size of 0.0–0.5 mm, and pre-dried to remove moisture. Pyrolysis experiments were carried out in a cylindrical carbon-steel reactor heated electrically to 400 °C and 500 °C under a continuous nitrogen atmosphere to maintain inert conditions. Four biomass-to-zeolite Y catalyst ratios (100/0, 95/5, 90/10, and 85/15 wt.%) were evaluated to study the effect of catalyst loading on product distribution. The scope of the present study was the physicochemical and fuel property characterisation of the bio-oil produced, rather than a mechanistic investigation of the catalyst itself. The zeolite Y catalyst used in this study was a commercially obtained material, and its role was evaluated through the observed changes in bio-oil properties rather than through direct catalyst surface analysis. The yields of bio-oil, biochar, and syngas were quantified by mass balance, while statistical analyses, including descriptive statistics and two-way ANOVA, were applied to assess the significance of temperature and catalyst ratio on product yield. Optimization of bio-oil yield was performed using a desirability function approach to identify the best operating conditions. The physicochemical and fuel properties of the produced bio-oils including viscosity, density, flash point, pour point, cloud point, pH, and higher heating value (HHV); were determined in accordance with ASTM standards of ASTM D445, ASTM D2270, ASTM D 792, ASTM D4052, ASTM D93, ASTM D97 and ASTM D2500 (Adegoke et al., 2021; Adeyemi et al., 2021; Camur and Alassi, 2021). These procedures provided comprehensive data for evaluating the influence of catalytic pyrolysis conditions on the fuel quality and energy potential of *Achyranthes aspera* -derived bio-oil.

A. Biomass Sample Collection

The biomass feedstock used in this study was *Achyranthes aspera* wood residue, collected from Ota in the Ado–Odo Local Government Area of Ogun State, Nigeria. This particular biomass was selected due to its abundance in the region and its current underutilization as an energy resource. Despite its wide availability, limited research exists on the physicochemical and fuel properties of bio-oil derived from *Achyranthes aspera* wood residue. Utilizing this biomass therefore presents a valuable opportunity to convert a low-value agricultural residue into a potential renewable energy source, contributing to waste minimization and sustainable biofuel production.

B. Sample Preparation

The collected *Achyranthes aspera* wood residue was processed to ensure uniform particle size and enhance heat transfer efficiency during pyrolysis. The biomass was first milled using equipment available in the Mechanical Central Workshop of Bells University of Technology, Ota, Nigeria. The milled material was then sieved to obtain a uniform particle size fraction within the range of 0.0–0.5 mm (500 μm). This size range was chosen to promote homogeneous heating and consistent thermal decomposition during the pyrolysis process. The prepared samples were subsequently weighed according to predetermined charge masses for each experimental run. A representative portion of the sample was pelletized and subjected to bomb calorimetric analysis to determine its higher heating value (HHV), which served as a baseline for assessing energy enhancement after catalytic pyrolysis.

C. Experimental Setup

The pyrolysis experiments were conducted using a laboratory-scale fixed-bed pyrolysis reactor fabricated from carbon steel. The reactor was electrically heated with a 4kW furnace capable of achieving uniform temperature control within the reaction chamber. A type-K thermocouple connected to a digital temperature controller was used to monitor and regulate the reactor temperature throughout each run. Prior to every experiment, the reactor was purged with high-purity nitrogen gas at a flow rate of 100 mL min^{-1} for 10 minutes to eliminate residual oxygen and establish an inert environment. During pyrolysis, a continuous nitrogen flow of 15 mL min^{-1} was maintained to prevent oxidation of the biomass and to ensure a consistent pyrolytic atmosphere.

The *Achyranthes aspera* wood residue was preheated at 103 °C for one hour to remove physically bound moisture. The pyrolysis process was then carried out at two target temperatures, 400 °C and 500 °C, each maintained for a residence time of 30 minutes or until the cessation of gas evolution. The condensable vapors released during thermal decomposition were passed through an ice-cooled condenser to collect the liquid bio-oil, while the remaining solid fraction was recovered as biochar. Non-condensable gases were vented and quantified by difference through mass balance calculations. The schematic configuration of the pyrolysis system and its experimental setup are illustrated in Figures 1 and 2 (Oyebanji et al., 2023).

D. Experimental Procedure

The pyrolysis experiments were designed to investigate the effect of catalyst loading and temperature on the yield distribution of *Achyranthes aspera* pyrolysis products. Four biomass-to-zeolite Y catalyst ratios; 100/0, 95/5, 90/10, and 85/15 wt.%; were tested under identical reaction conditions at 400 °C and 500 °C. In each experimental run, the weighed feedstock mixture was introduced into the reactor, and nitrogen gas was supplied continuously at a flow rate of 15 mL min^{-1} to maintain an inert environment throughout the process.

After the reaction, the resulting products were separated into three distinct fractions: bio-oil (liquid condensate), biochar (solid residue), and syngas (non-condensable gases). The masses of the bio-oil and biochar were measured directly using an analytical balance, while the syngas yield was determined by difference using a mass balance approach. The product yields were computed using the following relationships:

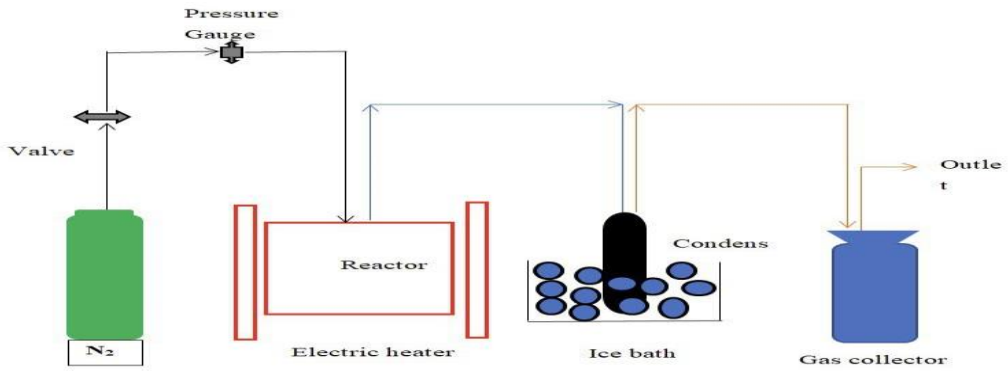
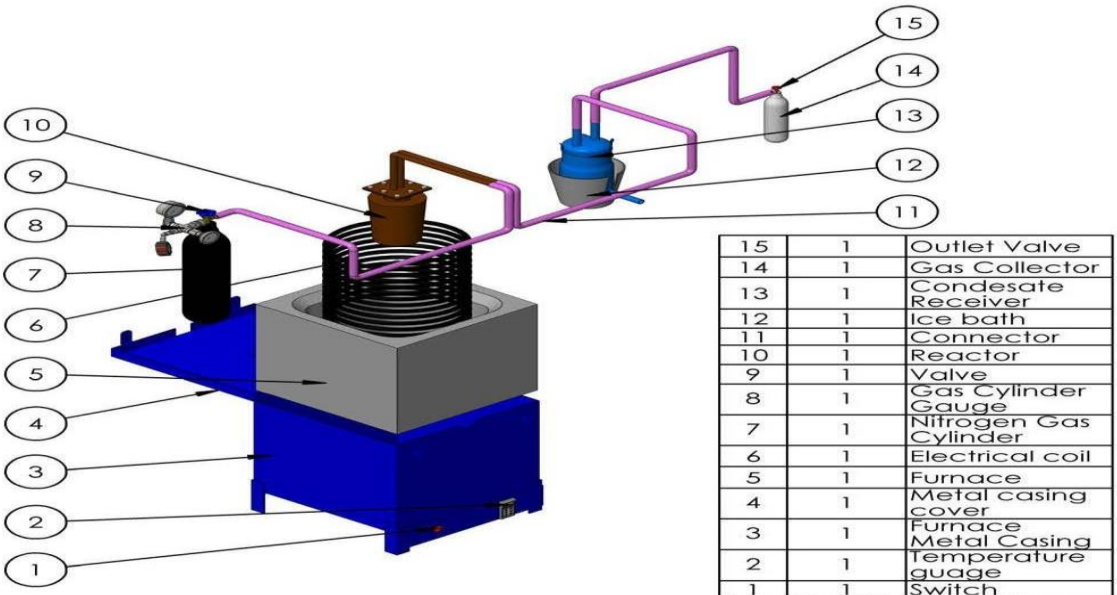


Figure 1. Schematic diagrams of pyrolysis apparatus.



Item	Quantity	Part Name
15	1	Outlet Valve
14	1	Gas Collector
13	1	Condesate Receiver
12	1	Ice bath
11	1	Connector
10	1	Reactor
9	1	Valve
8	1	Gas Cylinder Gauge
7	1	Nitrogen Gas Cylinder
6	1	Electrical coil
5	1	Furnace
4	1	Metal casing cover
3	1	Furnace Metal Casing
2	1	Temperature guage
1	1	Switch

Partlist Table

Figure 2. Pyrolysis experimental setup.

$$\%W_{Bio-oil} = \frac{W_{Bio-oil}}{W_{Biomass}} \times 100\% \quad (1)$$

$$\%W_Biochar = W_Biochar/W_Biomass \ x\ 100\% \quad (2)$$

$$\%W_Syngas = \ 100\% - (\%W_(Bio - oil) + \ \%W_Biochar\ ) \quad (3)$$

Where $W_{Biomass}$, $W_{Bio-oil}$, $\%W_{Biochar}$ and $\%W_{Syngas}$ represent the initial mass of the feedstock, mass of bio-oil, mass of biochar, and mass of syngas respectively.

Each experiment was conducted under steady-state heating and inert gas flow conditions to ensure repeatability and comparability of results. The product distribution data were subsequently analyzed to determine the influence of process parameters (temperature and catalyst ratio) on bio-oil yield and selectivity.

Non-condensable gases (syngas fraction) were quantified by mass balance. Gas composition analysis was beyond the scope of the current study due to the absence of online gas chromatographic equipment during experimental runs. Syngas yield values reported herein therefore represent total non-condensable gas mass fractions only, and do not include compositional data for individual gas species (CO, CO_2, CH_4, H_2).

E. Statistical Analysis

Statistical analysis was conducted to evaluate the influence of process parameters specifically pyrolysis temperature and biomass-to-catalyst ratio on the yield distribution of products obtained from the catalytic pyrolysis of *Achyranthes aspera* wood residue. Both descriptive and inferential statistical methods were employed to ensure a comprehensive interpretation of the experimental results. Descriptive statistics were used to summarize the variability and central tendency of bio-oil, biochar, and syngas yields across different experimental conditions, while inferential analysis using two-way analysis of variance (ANOVA) was performed to determine the statistical significance of temperature and catalyst loading on product selectivity. This analytical approach enabled an objective assessment of the reproducibility, consistency, and overall performance of the catalytic pyrolysis process, providing quantitative insight into the parameters most influential in optimizing bio-oil yield.

E.1. Descriptive Statistics

Descriptive statistical analysis was performed to summarize the central tendency and variability of the experimental data obtained from the pyrolysis process. Parameters such as the mean, standard deviation, variance, minimum, and maximum values were computed for the yields of bio-oil, biochar, and syngas under each experimental condition. These metrics provided insights into the data distribution, reproducibility, and consistency of the results across varying temperatures and catalyst ratios.

E.2. Experimental Design

To determine the significance of temperature and biomass-to-catalyst ratio on product yield distribution, a two-way analysis of variance (ANOVA) was employed. The independent variables were biomass-to-catalyst ratio (four levels: 100/0, 95/5, 90/10, and 85/15) and pyrolysis temperature (two levels: 400 °C and 500 °C), while the dependent variables were the yields of bio-oil, biochar, and syngas.

It is acknowledged that the current ANOVA analysis is based on a single observation per treatment combination for product yield data, which constrains the estimation of experimental error. In the absence of true within-treatment replication, the interaction term (Ratio × Temperature) was used as a proxy error term, following the approach described by Montgomery (2017) for unreplicated factorial designs. This method provides a conservative basis for detecting main effects but cannot independently verify reproducibility. Future investigations should employ a minimum of three replicate runs per treatment combination to enable proper error partitioning and improve statistical confidence.

Due to the single observation per treatment combination, the interaction term between temperature and catalyst ratio was used as a proxy error term for the F-test. Statistical significance was evaluated at a confidence level of $\alpha = 0.05$. The ANOVA results provided quantitative insight into which process parameters significantly influenced product selectivity and yield optimization during catalytic pyrolysis.

F. Bio-oil Yield Optimization

Optimization of bio-oil yield was performed using a desirability function approach to determine the most favorable operating conditions for catalytic pyrolysis of *Achyranthes aspera* wood residue. The optimization was designed to maximize the proportion of liquid bio-oil while minimizing the formation of biochar and syngas, thereby improving overall process efficiency.

Individual desirability functions were assigned to each response variable bio-oil, biochar, and syngas; based on their respective optimization objectives. These individual desirability values were then combined using a weighted geometric mean to obtain a single composite desirability index for each experimental run. Weighting factors of 0.5, 0.25, and 0.25 were applied to bio-oil, biochar, and syngas, respectively, reflecting the higher priority given to maximizing liquid fuel production.

The optimization model provided a systematic means of evaluating the combined effects of biomass-to-catalyst ratio and pyrolysis temperature on product distribution. This approach established the analytical framework for identifying the experimental condition with the highest overall desirability, which was later presented and discussed in the results section.

G. Determination of Bio-oil Physicochemical and Fuel Properties

The physicochemical and fuel properties of the bio-oil obtained from the catalytic pyrolysis of *Achyranthes aspera* wood residue were determined in accordance with standard analytical procedures established by the American Society for Testing and Materials (ASTM). The analyses were conducted to evaluate the suitability of the produced bio-oil as an alternative liquid fuel and to assess the influence of catalyst loading and temperature on its quality attributes.

The measured properties included kinematic viscosity, density, API (American Petroleum Institute) gravity, flash point, pour point, cloud point, and pH, all of which are critical indicators of fuel performance, storage stability, and handling safety. Viscosity was determined using a viscometer following ASTM D445, while the viscosity index was evaluated according to ASTM D2270 (Camur and Alassi, 2021). Density measurements were performed using a Pear DMA 4500 density meter in compliance with ASTM D4052. The flash point was obtained using an Abel flash point apparatus (ASTM D93), and the pour point and

cloud point were determined using a test jar, thermometer, and temperature chamber in line with ASTM D97 and ASTM D2500, respectively (Adeyemi et al., 2021; Wada et al., 2025). The pH of the bio-oil samples was measured using a calibrated digital pH meter as prescribed by ASTM D7946-19 (Asfaw et al., 2025).

The higher heating value (HHV) of both the raw biomass and the resulting bio-oil was estimated from the ultimate analysis using a correlation equation developed by (Oyebanji et al., 2018):

$$HHV_{DRY}(MJ/kg) = -1.3675 + 0.3137C + 0.7009H + 0.0318O \quad (4)$$

Where H.H.V (MJ/kg), C, H, and O represent Higher Heating Value, Carbon, Hydrogen, and Oxygen contents (on a dry basis) of the sample, respectively. These analyses provided a comprehensive dataset for assessing the thermochemical characteristics and energy potential of the bio-oil, forming the basis for comparison with conventional petroleum fuels and other biomass-derived oils.

III. RESULTS AND DISCUSSIONS

This section presents and discusses the results obtained from the catalytic pyrolysis of *Achyranthes aspera* wood residue at temperatures of 400 °C and 500 °C under varying biomass-to-zeolite Y catalyst ratios (100/0, 95/5, 90/10, and 85/15). The analysis focuses on the distribution of pyrolysis products (bio-oil, biochar, and syngas) and the physicochemical and fuel properties of the produced bio-oil. The results are interpreted to elucidate the effects of temperature and catalyst loading on product yield, energy content, and fuel quality.

The discussion integrates statistical analyses, including descriptive and inferential evaluations, to identify significant process parameters influencing product selectivity. Furthermore, the findings are compared with relevant literature to highlight similarities, deviations, and possible explanations for observed trends. Overall, this section provides a comprehensive interpretation of how catalytic pyrolysis conditions influence the conversion efficiency and fuel characteristics of *Achyranthes aspera* -derived bio-oil, emphasizing its potential as a sustainable and renewable energy resource.

It is noted that the present study focuses exclusively on the physicochemical and fuel properties of the produced bio-oil. Chemical compositional analysis by GC-MS, including identification of functional groups, organic acid content, phenolic fractions, and hydrocarbon profiles, has been conducted as part of a companion study and will be reported separately. This division of scope ensures the completeness and depth of reporting for each analytical domain.

A. Effect of Temperature and Catalyst Loading on Product Yield Distribution

Table 1 and Figures 3 and 4 present the effects of pyrolysis temperature and biomass-to-zeolite Y catalyst ratio on the yield distribution of bio-oil, biochar, and syngas derived from *Achyranthes aspera* wood residue. The results demonstrate that both temperature and catalyst loading significantly influenced product distribution, with notable variations in the relative proportions of the three fractions.

At 400 °C, the highest bio-oil yield (43.00 wt.%) was obtained at a biomass-to-catalyst ratio of 95/5, while the lowest bio-oil yield (33.60 wt.%) occurred at a ratio of 85/15. The biochar yield ranged from 20.35 wt.% to 30.65 wt.%, decreasing with increasing temperature and catalyst concentration beyond the 10% level. Conversely, syngas yield increased progressively with higher catalyst loading, rising from 28.90 wt.% at 100/0 to 46.05 wt.% at 85/15. This trend indicates that higher catalyst proportions favor secondary cracking reactions, enhancing gas formation at the expense of liquid and solid yields which is similar to the report of Putun (2010).

At 500 °C, similar behavior was observed, although overall bio-oil yields were higher than those at 400 °C, confirming that elevated temperatures promote thermal decomposition and volatile release. The maximum bio-oil yield of 52.95 wt.% was recorded at the 95/5 ratio, after which further increases in catalyst loading reduced the liquid yield while increasing syngas production. This result suggests an optimal catalytic threshold beyond which excessive cracking diminishes condensable hydrocarbons. Correspondingly, biochar yield decreased steadily with temperature, consistent with enhanced

volatilization and secondary decomposition reactions at higher thermal input. The results revealed that Bio-oil and syngas increase, meanwhile biochar yield decreases with increased pyrolysis temperature which is consistent with the findings of Imam and Capareda (2012), Makavana et al. (2020).

Overall, the results reveal a clear temperature–catalyst interaction effect, where moderate catalyst loading combined with elevated temperature enhances bio-oil formation, while excessive catalyst levels promote gas generation. These observations are consistent with literature reports on zeolite-catalyzed pyrolysis, where catalysts facilitate deoxygenation and cracking reactions that convert heavier organic intermediates into lighter gaseous compounds.

Figure 1 illustrates the product yield trends at 400 °C, showing that bio-oil predominates at lower catalyst loadings, while Figure 2 depicts a similar pattern at 500 °C with higher total volatile conversion. Collectively, these findings confirm that optimal bio-oil yield from *Achyranthes aspera* wood residue is achieved under moderate catalytic influence at elevated temperature, striking a balance between volatilization and secondary cracking.

These findings are broadly consistent with the established literature on biomass pyrolysis. Studies confirm that temperatures in the range of 400–600 °C result in maximum bio-oil yield across different reactor types, while excessively high temperatures promote secondary cracking reactions that increase gas yield, and low temperatures favour char formation (Reza et al., 2023). The feedstock-dependence of the optimal temperature is also well documented; for instance, beauty leaf fruit husk reached its highest bio-oil yield of 44.2% at 500 °C during fast pyrolysis, while sugarcane bagasse and wheat straw peaked at 550 °C, and rice straw at 450 °C (Maulinda et al., 2023a), which explains why *Achyranthes aspera* residue achieved its optimum at 500 °C in the present study. The impact of zeolite Y catalyst loading is equally supported: at higher catalyst loadings, biochar and syngas yields increase while bio-oil yields decrease, because catalytic cracking of heavier oxygenated vapours shifts the product balance toward non-condensable gases; a pattern directly observed at the 85/15 ratio in this study (Reza et al., 2023).

The yield trade-off with increasing catalyst ratio is therefore consistent with established catalytic cracking behaviour, and the maximum yield of 52.95 wt.% at 95/5 and 500 °C exceeds the 40–48 wt.% range reported by Nanda et al. (2014) for high-heating-rate pyrolysis of lignocellulosic biomasses at 450 °C, further confirming the upgrading benefit of zeolite Y. The decrease in biochar yield with temperature observed in the present study is also consistent with Nanda et al. (2014), who reported biochar yields of 21–24 wt.% under high heating rate conditions, broadly comparable to the 17.05–30.65 wt.% range obtained in this study. Furthermore, Pütün (2010), already cited in this study, reported bio-oil yields of 41%, 46%, and 43% at 400 °C, 550 °C, and 700 °C respectively using MgO catalyst, which are lower than the 52.95 wt.% achieved in the present study at 500 °C with zeolite Y at 95/5 ratio, further attributing the higher yield to the selective condensable vapour formation promoted by zeolite Y catalysis.

Table 1. Effect of temperatures and catalysts on product yield.

	Temperature, 400°C			Temperature, 500°C		
Biomass-to-Catalyst Ratios	Bio-Oil (wt.%)	Biochar (wt.%)	Syngas (wt.%)	Bio-Oil (wt.%)	Biochar (wt.%)	Syngas (wt.%)
100/0	42.55	28.55	28.90	51.85	25.75	22.40
95/5	43.00	27.75	29.25	52.95	22.00	25.05
90/10	37.85	30.65	31.50	46.75	21.30	31.95
85/15	33.60	20.35	46.05	29.45	17.05	53.50

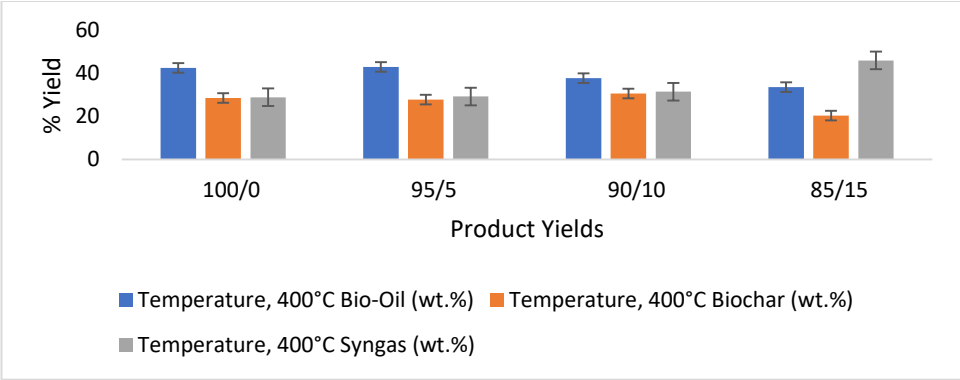


Figure 3. Product Yield of the Biomass-to-Zeolite Y Catalyst Ratios at 400°C.

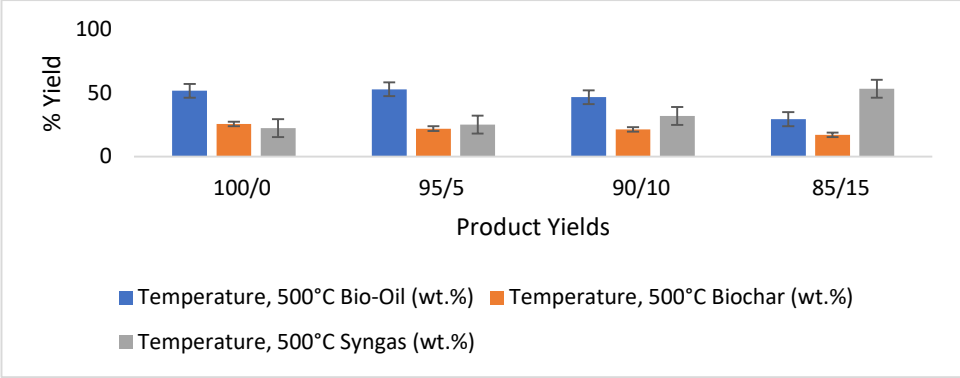


Figure 4. Product Yield of the Biomass-to-Zeolite Y Catalyst Ratios at 500°C.

B. Statistical Evaluation of Product Yield Distribution

B.1. Descriptive Analysis of Product Yields

Tables 2 and 3 present the statistical summary of product yields for the pyrolysis of *Achyranthes aspera* wood residue at different temperatures and biomass-to-catalyst ratios, respectively. The descriptive statistics show clear variations in product distribution, confirming that both temperature and catalyst concentration influence the proportions of bio-oil, biochar, and syngas.

As shown in Table 2, increasing the temperature from 400 °C to 500 °C generally enhanced bio-oil yield while reducing biochar production. The mean bio-oil yield increased from 39.25 wt.% to 45.25 wt.%, indicating more efficient conversion of biomass into liquid products at higher temperatures. In contrast, mean biochar yield decreased from 26.82 wt.% to 21.52 wt.%, consistent with enhanced devolatilization and secondary decomposition reactions. Syngas yield remained relatively high across both temperatures, with greater variability (CV ≈ 30%) suggesting stronger dependence on catalyst loading.

Table 3 summarizes the effect of catalyst ratio on product yield distribution. The bio-oil yield peaked at a biomass-to-catalyst ratio of 95/5, whereas higher catalyst loadings (90/10 and 85/15) promoted syngas formation, reflecting the catalytic cracking of heavier vapors into gaseous hydrocarbons. The relatively low variation in biochar yield across treatments implies that the solid fraction was less sensitive to moderate changes in catalyst ratio.

Figures 5–7 further illustrate these trends. The interaction plots show non-parallel lines between temperature and catalyst ratio, indicating the presence of a significant interaction effect. Specifically, the interaction plot for bio-oil (Figure 5) demonstrates that the positive temperature effect on yield was most pronounced at moderate catalyst loadings (95/5). For biochar (Figure 6), yield decreased consistently with temperature, while for syngas (Figure 7), yields increased sharply with higher catalyst concentrations, particularly at elevated temperature. These relationships confirm that both process parameters jointly determine product selectivity during catalytic pyrolysis.

Table 2. Statistics by temperature on the product yield of the pyrolysis of the biomass.

	Temperature, 400°C			Temperature, 500°C		
Statistics	Bio-Oil (wt.%)	Biochar (wt.%)	Syngas (wt.%)	Bio-Oil (wt.%)	Biochar (wt.%)	Syngas (wt.%)
Mean	39.25	26.82	33.92	45.25	21.52	33.23
Standard Deviation	3.84	3.89	7.07	9.42	3.09	12.21
Variation	14.71	15.10	50.00	88.69	9.54	149.18
Minimum	33.60	20.35	28.90	29.45	17.05	22.40
Maximum	43.00	30.65	46.05	52.95	25.75	53.50
Range	9.40	10.30	17.15	23.50	8.70	31.10

Table 3. Statistics by biomass-to-catalyst ratio on the product yield of the pyrolysis of the biomass.

Biomass-to-Catalyst Ratios	Product Yields	Mean	Standard Deviation	Variation	Minimum	Maximum	Range
100/0	Bio-oil	47.20	4.62	21.62	42.55	51.85	9.30
	Biochar	27.15	1.40	1.96	25.75	28.55	2.80
	Syngas	25.65	3.25	10.56	22.40	28.90	6.50
95/5	Bio-oil	47.98	4.98	24.75	43.00	52.95	9.95
	Biochar	24.88	2.86	8.27	22.00	27.75	5.75
	Syngas	27.15	2.10	4.41	25.05	29.25	4.20
90/10	Bio-oil	42.30	4.45	19.80	37.85	46.75	8.90
	Biochar	25.98	4.67	21.86	21.30	30.65	9.35
	Syngas	31.73	0.22	0.05	31.50	31.95	0.45
85/15	Bio-oil	31.52	2.08	4.31	29.45	33.60	4.15
	Biochar	18.70	1.65	2.72	17.05	20.35	3.30
	Syngas	49.77	3.73	13.88	46.05	53.50	7.45

B.2. Inferential Analysis of Process Effects (ANOVA Results)

Tables 4–6 present the two-way ANOVA results for bio-oil, biochar, and syngas yields, respectively. The analysis revealed that neither temperature nor catalyst ratio had a statistically significant effect on bio-oil yield at the 95% confidence level (Table 4). This indicates that within the experimental range studied, both parameters influence bio-oil production qualitatively but not at a statistically significant level, likely due to the limited number of experimental replicates.

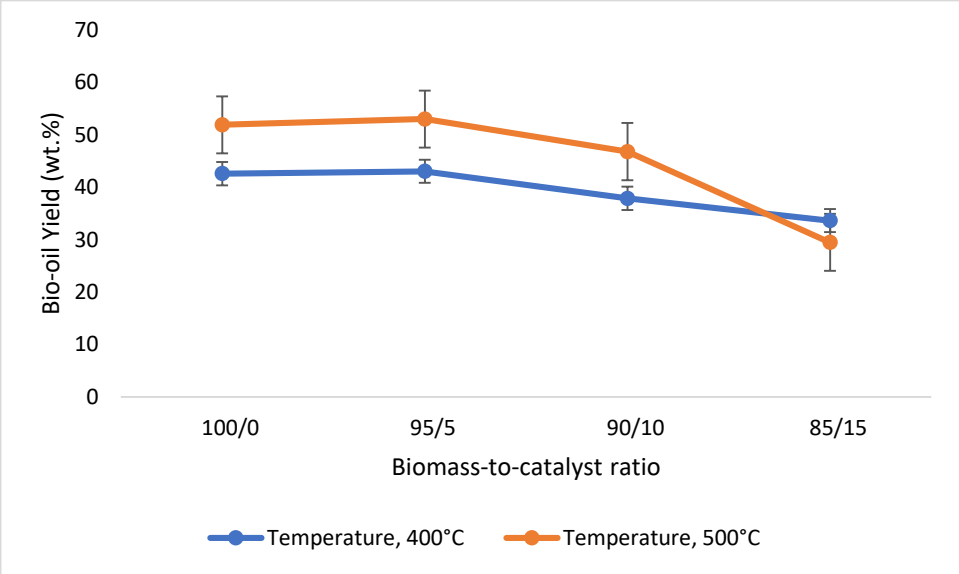


Figure 5. indicates the interaction plot of the bio-oil yields by biomass-to-catalyst ratio and temperature of the pyrolysis of the biomass.

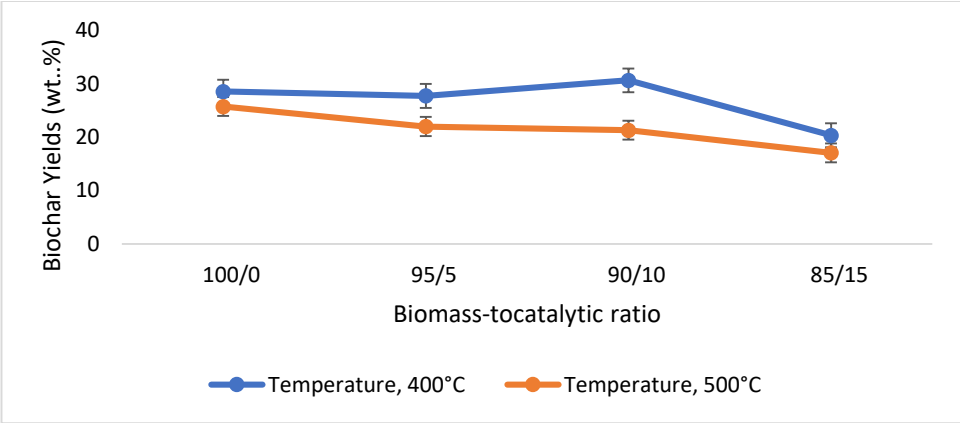


Figure 6. shows the interaction plot of the biochar yields by biomass-to-catalyst ratio and temperature of the pyrolysis of the biomass.

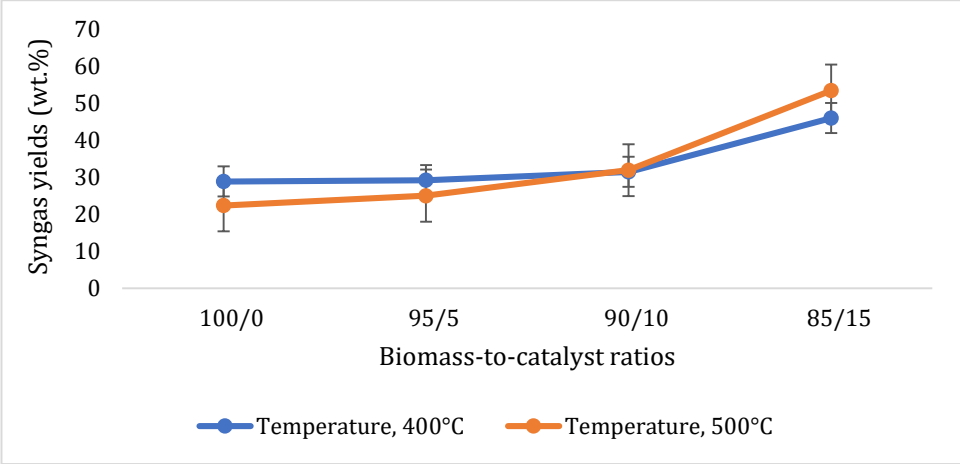


Figure 7. indicates the interaction plot of the syngas yields by biomass-to-catalyst ratio and temperature of the pyrolysis of the biomass.

For biochar yield (Table 5), the effect of temperature was found to be significant ($p < 0.05$), confirming that thermal intensity is a major determinant of solid residue formation. However, catalyst ratio showed no significant influence, suggesting that solid yield was primarily governed by thermal decomposition rather than catalytic reactions. In contrast, for syngas yield (Table 6), the biomass-to-catalyst ratio exerted a significant effect ($p < 0.05$), while temperature did not. This outcome indicates that catalyst concentration plays a key role in secondary cracking reactions that enhance gas evolution.

Table 4. Two-Way ANOVA Table for Bio-Oil.

Source	Degree of Freedom	Sum of Square	Mean of Square	F-value	F-critical	Significant
Ratio (Factor A)	3	344.6125	114.8708	4.9971	9.28	Not Significance
Temperature (Factor B)	1	72.0000	72.0000	3.1321	10.13	Not Significance
Ratio × Temperature	3	68.9625	22.9875			Used as Error
Error	0	0.0000	-			
Total	7	485.5750	-			

Note: $df_{error} = 0$. Interaction term was used as proxy for error

Table 5. Two-Way ANOVA Table for Biochar.

Note: $df_{error} = 0$. Interaction term was used as proxy for error

Source	Degree of Freedom	Sum of Square	Mean of Square	F-value	F-critical	Significant
Ratio (Factor A)	3	85.1125	28.3708	6.3387	9.28	Not significance
Temperature (Factor B)	1	56.1800	56.1800	12.5519	10.13	Significance
Ratio × Temperature	3	13.4275	4.4758			Used as Error
Error	0	0.0000	-			
Total	7	154.7200	-			

Note: $df_{error} = 0$. Interaction term was used as proxy for error

Table 6. Two-Way ANOVA Table for Biochar.

Source	Degree of Freedom	Sum of Square	Mean of Square	F-value	F-critical	Significant
Ratio (Factor A)	3	739.8975	246.6325	13.0224	9.28	Significance
Temperature (Factor B)	1	0.9800	0.9800	0.0517	10.13	Not Significance
Ratio × Temperature	3	56.8175	18.9392			Used as Error
Error	0	0.0000				
Total	7	797.6950				

Note: $df_{error} = 0$. Interaction term was used as proxy for error

Table 7. Comparative descriptive statistics: all product yield of the pyrolysis of the biomass.

Product Yields	N	Mean (wt.%)	Standard Deviation	Variance	Minimum	Maximum	Range	CV (%)
Bio-oil	8	42.25	7.79	60.70	29.45	52.95	23.50	18.44
Biochar	8	24.18	4.40	19.34	17.05	30.65	13.60	18.20
Syngas	8	33.58	9.99	99.71	22.40	53.50	31.10	29.75

Table 7 summarizes the comparative descriptive statistics for all products. The coefficient of variation (CV) was highest for syngas (29.75%), indicating greater fluctuation and sensitivity to process changes, while bio-oil and biochar exhibited lower variability (approximately 18%). These statistical findings support the earlier observation that moderate catalyst loading and elevated temperature favor bio-oil formation, while excessive catalyst levels promote syngas generation.

C. Optimization of Bio-oil Yield

Table 8 and Figure 9 present the optimization results for the catalytic pyrolysis of *Achyranthes aspera* wood residue based on the desirability function approach. The optimization was aimed at maximizing bio-oil yield while minimizing biochar and syngas production, thereby improving the efficiency of liquid fuel generation.

The desirability ranking shown in Table 8 indicates that both temperature and biomass-to-catalyst ratio exerted a strong combined influence on the overall process performance. The optimal condition corresponded to a biomass-to-catalyst ratio of 95/5 at 500 °C, which produced the highest composite desirability score. This condition achieved a favorable balance between thermal decomposition and catalytic cracking, promoting the formation of condensable volatiles while limiting excessive gasification.

As reflected in Figure 9, the overall desirability trend decreased progressively at higher catalyst loadings (90/10 and 85/15), illustrating that excessive catalyst concentrations shift the reaction toward secondary cracking and non-condensable gas formation. In contrast, lower catalyst levels (100/0) resulted in reduced liquid yields due to insufficient catalytic deoxygenation. Therefore, moderate catalyst

addition under high-temperature conditions provided the most efficient reaction environment for maximizing liquid bio-oil yield.

These findings are consistent with similar studies on zeolite-catalyzed pyrolysis, where optimized catalyst loading enhances vapor-phase reactions, improves bio-oil quality, and minimizes coke deposition. The statistical optimization thus confirms that *Achyranthes aspera* wood residue can serve as an effective renewable feedstock for high-yield bio-oil production when processed under properly balanced catalytic and thermal conditions. The optimal biomass-to-catalyst and temperature for the pyrolysis of the *Achyranthes aspera* wood residue are 95/5 and 500°C respectively with the highest overall desirability score of 88.77 which yielded 52.95 wt.% Bio-oil, 22.00 wt.% Biochar, and Syngas wt.%. This result conforms to the report Makavana et al. (2020), Maulinda et al. (2023a), Jamilatun et al., (2020) but contradict the findings of Rohim et al. (2014), Maulinda et al. (2023b) where maximum bio-oil yield was obtained at a temperature of 400°C. The different results may be as a result of different in biomass pyrolysis.

Table 8. Operating Conditions Performance Ranking.

Rank	Biomass-to-catalyst ratio	Temperature	Bio-oil (wt.%)	Biochar (wt.%)	Syngas (wt.%)	Overall Desirability
1	95/5	500°C	52.95	22.00	25.05	88.77
2	100/0	500°C	51.85	25.75	22.40	81.67
3	90/10	500°C	46.75	21.30	31.95	71.32
4	95/5	400°C	43.00	27.75	29.25	53.65
5	100/0	400°C	42.55	28.55	28.90	51.51
6	90/10	400°C	37.85	30.65	31.50	35.36
7	85/15	400°C	33.60	20.35	46.05	33.75
8	85/15	500°C	29.45	17.05	53.50	25.00

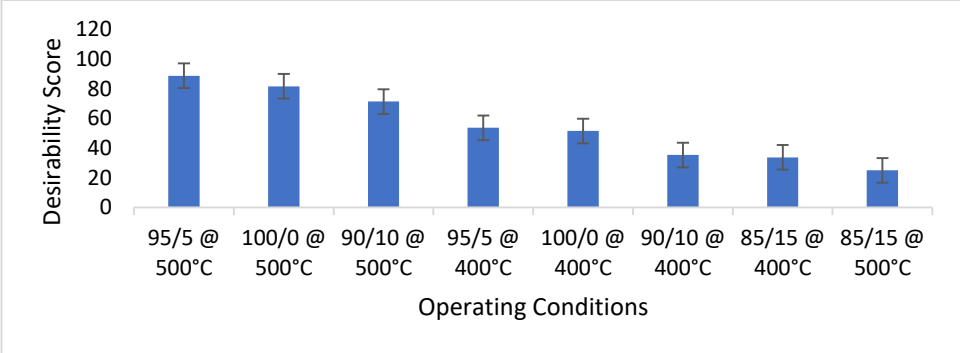


Figure 8. Desirability scores comparison.

D. Bio-oil Fuel Properties

The basic fuel characteristics of the bio-oil obtained at biomass-to-catalyst ratios of biomass/catalyst ratios of 100/0, 95/5, 90/10, and 85/15 and pyrolysis temperature of 400°*C* and 500°C were discussed in this part, including the flash point, pour point, pH level, density, viscosity, and cloud point.

D.1. Flash Point

The flash point is an important property of a fuel, as it indicates the temperature at which the fuel can ignite and poses a fire hazard. Table 9 shows the flash points of bio-oils obtained from pyrolysis of *Achyranthes aspera* at different biomass/catalyst ratios using ASTM D92 and ASTM D93. According to Table 9, the flash points of bio-oils produced from the pyrolysis of biomass at 400°C with biomass/catalyst ratios of 100/0, 95/5, 90/10, and 85/15 were 82°C, 80°C, 82°C, and 80°C, respectively. Similarly, at 500°C (Table 9), the flash points for the same ratios were 82°C, 78°C, 76°C, and 76°C. In comparison, the flash point of diesel fuel is 50°C (Selvaraj et al., 2020). The higher flash point values for bio-oils compared to petroleum diesel fuel indicates better stability and safety for the bio-oils with less volatile and more stable components, likely due to the presence of phenolic or alcoholic compounds.

Across both pyrolysis temperatures (400°C and 500°C), all bio-oil samples demonstrated flash points considerably higher than conventional diesel fuel (50°C), ranging from 76°C to 82°C, which is consistent with the findings of Russo et al. (2023). This represents a meaningful safety advantage, as higher flash points indicate reduced fire hazard and greater handling safety during storage and transport. From a practical standpoint, these bio-oils would be classified as less flammable under standard hazard classifications compared to diesel, making them safer for tropical-region handling conditions. This finding is further supported by Wada et al. (2025), who reported a flash point of 128°C for Lannea microcarpa biodiesel well above the ASTM D6751 minimum of 100°C and similarly attributed the high flash point to reduced volatility of the fuel fractions. In contrast, Okekunle et al. (2021) reported flash points of only 32–48°C for catalytic pyrolysis bio-oils from Tectona grandis using MgO catalyst values lower than petroleum diesel indicating that the choice of catalyst strongly influences the flash point outcome. The notably higher flash points of the *Achyranthes aspera* bio-oils (76–82°C) in the present study, compared with the Tectona grandis values, may be attributed to the selective deoxygenating action of zeolite Y, which preferentially eliminates low-boiling-point oxygenated compounds while retaining heavier, thermally stable fractions. Adeyemi et al. (2021) also reported a flash point of 103°C for Sand Apple ethyl ester, confirming that bio-oils and biodiesels derived from underutilised tropical biomass feedstocks consistently exhibit flash points exceeding that of petroleum diesel, which is an important safety feature for developing-country applications.

Regarding the effect of catalyst loading, there is a modest but discernible trend at 500°C where increasing the catalyst ratio from 100/0 to 90/10 and 85/15 progressively lowers the flash point from 82°C to 76°C. This suggests that catalytic activity is influencing the composition of the bio-oil, likely promoting the formation of lighter, more volatile fractions through cracking reactions. The effect is less pronounced at 400°C, where flash points fluctuate narrowly between 80°C and 82°C, indicating that the lower pyrolysis temperature limits the extent of catalytic cracking.

The observed temperature dependency confirms that pyrolysis temperature exerts a more pronounced influence on flash point than catalyst concentration within the investigated range. This aligns with findings in biomass pyrolysis literature, where increasing reactor temperature typically shifts product distribution toward lighter compounds, consequently reducing flash point due to higher volatility.

However, while a higher flash point enhances safety, it may also indicate lower volatility, which can influence atomization quality and cold-start performance in compression ignition engines. Overall, the findings indicate that (i) pyrolysis temperature is the dominant factor affecting flash point, (ii) catalyst loading up to 15% produces only marginal reductions in flash point, and (iii) the produced bio-oils exhibit superior safety characteristics compared to conventional diesel fuel. These results support the potential applicability of the bio-oils for safe storage and handling, while highlighting the need for further optimization and upgrading if engine compatibility is to be achieved.

Increasing the flash point of bio-oils is crucial for improving their safety and storage properties. Higher flash points mean lower fire hazards, making bio-oils more practical for widespread use. Notably, flash points between 60 – 93 °C classify a fuel as a Class IIIA combustible liquid rather than a flammable liquid, which has direct regulatory and handling implications for storage, transport, and safety cabinet requirements (Oasmaa et al., 2012; NFPA 30, 2021). All *Achyranthes aspera* bio-oil samples in this study fall within this range, confirming that they can be handled and stored under standard combustible liquid protocols rather than the more restrictive regulations for flammable liquids. Flash points ranging from 40 °C to above 100 °C have been reported for pyrolysis bio-oils, depending on feedstock and processing conditions (Stelmach et al., 2023). The values of 76–82 °C obtained in this study lie within the upper portion of reported range, which is consistent with catalytically upgraded bio-oils rather than crude fast-pyrolysis products that typically exhibit flash points of 40–50 °C.

D.2. Pour Point

The temperature below which a liquid loses its ability to flow is known as the pour point. According to Table 9, the pour points of bio-oils produced from the pyrolysis of biomass at 400°C with biomass/catalyst ratios of 100/0, 95/5, 90/10, and 85/15 were -4°C, -3°C, -3°C, and -3°C, respectively. Similarly, at 500°C (Table 9), the pour points for the same ratios were -4°C, -3°C, -3°C, and -3°C. In comparison, the pour point of diesel fuel is -2°C.The bio-oil pour point for *Achyranthes aspera* arranged from -4 to -3 °C; the highest value for each sample was at 100/0 biomass/catalyst ratio. These pour points were determined at the optimum pyrolysis temperatures (500 °C).

Table 9. Bio-oil fuel properties.

		Temperature, 400°C				Temperature, 500°C			
Properties	Diesel	100/0	95/5	90/10	85/15	100/0	95/5	90/10	85/15
Flash point	50 °C	82 °C	80 °C	82 °C	80 °C	82 °C	78 °C	76 °C	76 °C
Pour Point	−2 °*C*	−4 °C	−3 °C	−3 °C	−3 °C	−4 °C	−3 °C	−3 °C	−3 °C
pH	5.5-8.0	7.50	8.00	8.50	8.50	7.50	8.05	8.50	8.50
Density	0.78g/mL	0.78g/mL	0.85g/mL	0.82g/mL	0.81g/mL	0.78g/mL	0.85g/mL	0.82g/mL	0.81g/mL
Viscosity	1.50-4.00 cSt	4.30 cSt	4.00 cSt	4.01 cSt	4.01 cSt	4.30 cSt	4.00 cSt	4.00 cSt	4.00 cSt
API gravity	45.0-46.0	40.00	45.18	45.50	45.58	40.00	45.09	45.10	45.10

The pour points of -3°C (catalytic) and -4 °C (non-catalytic) for the *Achyranthes aspera* bio-oils indicate acceptable low-temperature fluidity for tropical and warm-temperate applications. These values are notably warmer (less negative) than the pour points reported for several other bio-oils and biodiesels in the literature, which typically range from -7 °C to -28 °C. For instance, Okekunle et al. (2021) reported pour points of -25 °C to -28 °C for catalytic pyrolysis bio-oils from Tectona grandis, and Wada et al. (2025) reported a pour point of -9.5 °C for *Lannea microcarpa* biodiesel. Binhweel et al. (2021), in a comparative review of biodiesels from eleven vegetative oil sources, reported pour points ranging from -18 °C (mustard biodiesel) to +14.33 °C (palm biodiesel), confirming that pour point is highly feedstock-dependent. The relatively higher pour points of the *Achyranthes aspera* bio-oils (-3 to -4 °C) compared with fast-pyrolysis bio-oils from temperate feedstocks may be attributable to the presence of higher molecular weight fractions and partially condensed oxygenated species in the slow-pyrolysis product. While this does not impair practical use in Nigeria and similar tropical climates, where ambient temperatures consistently exceed 25°C (well above the pour point), it represents a limitation for cold-region applications. Catalyst loading showed only marginal influence on pour point in this study (-4 °C at 100/0 to -3 °C at 95/5 and above), which is consistent with the observation of Okekunle et al. (2021) that catalyst presence has limited effect on pour point at certain temperatures, with pour point behaviour primarily governed by molecular weight distribution and wax content of the bio-oil fraction.

D.3. pH Value

The pH scale is used to determine how acidic and alkaline an aqueous solution or oil product is. According to ASTM D7946-19, Table 9, the pH values of bio-oils produced from the pyrolysis of biomass at 400°C with biomass/catalyst ratios of 100/0, 95/5, 90/10, and 85/15 are 7.50, 8.00, 8.50, and 8.50, respectively. Similarly, at 500°C (Table 9), the pH values for the same ratios are 7.50, 8.05, 8.50, and 8.50. In comparison, diesel fuel typically has a range of pH values between 5.5 and 8.0. The zeolite Y catalyst increased the bio-oils' pH levels at 400°C and 500°C pyrolysis temperature, as seen in the Table 9 which is similar the report of Campusano et al. (2024). The pH values of 7.50–8.50 obtained for the *Achyranthes aspera* bio-oils represent a marked departure from the typically acidic pH range of 2.0–3.8 reported for most pyrolysis bio-oils. Okekunle et al. (2021) reported pH values of 2.7–3.4 for both catalytic (MgO) and non-catalytic bio-oils from Tectona grandis well within the strongly acidic range and noted that these low

pH values cause corrosive damage to internal combustion engine components. This contrast highlights the exceptional deoxygenating effectiveness of zeolite Y compared to MgO, as the acid-site-driven catalytic activity of zeolite Y promotes decarboxylation and dehydration of carboxylic acids (principally acetic and formic acids, the primary contributors to bio-oil acidity), converting them to CO2 and H2O rather than retaining them in the liquid fraction. The progressive increase in pH with catalyst loading (from 7.50 at 100/0 to 8.50 at 85/15) confirms that higher zeolite Y concentration intensifies this deoxygenation effect. This finding is consistent with the report of Campusano et al. (2024), who similarly documented pH improvement in bio-oil following catalytic upgrading, and with Reza et al. (2023), who confirmed that zeolite-type catalysts are particularly effective in reducing oxygenated acid content in bio-oils. The near-neutral to slightly alkaline pH values reported in the present study have important practical implications: they indicate significantly reduced corrosion risk for storage containers, fuel lines, and engine components, improving the compatibility of *Achyranthes aspera* bio-oil with existing petroleum fuel infrastructure. This is a meaningful advantage over conventional bio-oils, whose acidity remains one of the principal barriers to direct application. The broader literature confirms the extent of this contrast: standard pyrolysis bio-oil pH typically ranges from 2.0 to 2.5 due to the abundance of water and oxygenated compounds, which prevents its direct use in fossil fuel-based infrastructures (Reza et al., 2023). Adegoke et al. (2021) similarly reported pH values of 3.11–3.93 for Gmelina arborea bio-oil strongly acidic across all temperatures studied confirming that the near-neutral pH achieved in the present study through zeolite Y catalysis is a genuinely distinctive outcome that substantially improves the practical usability of the bio-oil.

Maintaining a higher pH value in bio-oils is vital for reducing corrosive wear in engines and storage systems. Less acidic bio-oils lead to longer-lasting infrastructure and lower maintenance costs. The use of zeolite Y catalysts not only increases the pH value but also contributes to the production of bio-oils that are more compatible with existing fuel systems, thus facilitating a smoother transition to renewable energy sources.

D.4. pH Value

The density of an object is defined as the mass to volume ratio of the object. In a combustion system, different materials have different densities. Oil density is important and is related to the chemical makeup and composition of the oil. According to Table 9, the densities of bio-oils produced from biomass pyrolysis at 400°C varied with biomass/catalyst ratios: 100/0 (0.78 g/mL), 95/5 (0.85 g/mL), 90/10 (0.82 g/mL), and 85/15 (0.81 g/mL). Similarly, at 500°C (Table 9), the densities for these ratios were 100/0 (0.78 g/mL), 95/5 (0.85 g/mL), 90/10 (0.82 g/mL), and 85/15 (0.81 g/mL). In comparison, diesel fuel typically has a density around 0.78 g/mL. The slight variations in density with different biomass/catalyst ratios suggest that the introduction of zeolite Y catalysts during biomass pyrolysis has minimal impact on the overall density of bio-oils. This indicates that while catalysts may influence other properties such as acidity or ignition points, they do not significantly alter the mass per unit volume of the resulting bio-oils. The results revealed that an increase in catalyst in the biomass/catalyst ratios at both 400°C and 500°C decreases the density of the bio-oil produced which is similar to the findings of Budiman and Mulyono (2018).

The densities of 0.78–0.85 g/mL for the *Achyranthes aspera* bio-oils are substantially lower than values typically reported for conventional pyrolysis bio-oils, confirming effective deoxygenation by the zeolite Y catalyst. This finding is consistent with the report of Budiman and Mulyono (2018), who similarly documented density reduction in catalytically cracked bio-oil, and with Reza et al. (2023), who attribute the density reduction to removal of heavy oxygenated compounds. Critically, the densities obtained in this study are considerably lower than those reported by Wada et al. (2025) for Lannea microcarpa biodiesel (0.8965 g/cm^3) and by Binhweel et al. (2021), whose comparative review of eleven biodiesels reported densities ranging from 867 to 888.9 kg/m^3 (0.867–0.889 g/cm^3) for various vegetative oil-derived biodiesels. The lower density of the *Achyranthes aspera* bio-oil (0.78–0.85 g/mL) suggests a lighter hydrocarbon profile more closely resembling petroleum-derived fuels, which is

advantageous for injection system performance and air-fuel mixing in compression ignition engines. The results reveal that an increase in the catalyst ratio in the biomass/catalyst ratios at both 400°C and 500°C decreases the density of the bio-oil produced a trend consistent with progressive deoxygenation at higher catalyst concentrations, as confirmed by Budiman and Mulyono (2018). For broader context, the specific gravity of conventional pyrolysis bio-oil is reported to range from 1.10 to 1.25, meaning raw bio-oil is typically heavier than water and significantly heavier than petroleum distillates (Adegoke et al., 2021). The values of 0.78–0.85 g/mL obtained in this study fall well below this range, closer to light petroleum distillates, further confirming the substantial upgrading achieved by zeolite Y catalysis. Chukwuneke et al. (2022) reported a density of 0.951 g/mL for bio-oil from Swietenia macrophylla pyrolysis still considerably higher than the catalytic *Achyranthes aspera* bio-oil values reinforcing the superior deoxygenation performance of the zeolite Y system employed in this study.

D.5. Viscosity

Viscosity is a metric for a fluid's flow resistance. It speaks of the internal friction of a fluid in motion. Tables 9 displays the viscosity of bio-oil as the catalyst percentage is increased from 0 to 40%. Table 9 illustrates how the viscosity of bio-oils produced from biomass pyrolysis at 400°C varies with biomass/catalyst ratios: 100/0 (4.30), 95/5 (4.00), 90/10 (4.01), and 85/15 (4.01). Similarly, at 500°C (Table 9), the viscosities for these ratios were 100/0 (4.30), 95/5 (4.00), 90/10 (4.00), and 85/15 (4.00). In comparison, diesel fuel typically exhibits a viscosity ranging from 1.5 to 4.0. The Table 9 revealed that increase in catalyst in the biomass/catalyst ratios at both 400°C and 500°C decreases the viscosity of the bio-oil produced which is similar to the report of Budiman and Mulyono (2018), Reza et al. (2023). The minor variations in viscosity across different biomass/catalyst ratios suggest that while zeolite Y catalysts influence other properties such as acidity or flash points, they have limited impact on the flow characteristics of bio-oils. This indicates that viscosity is primarily dictated by the molecular composition of the bio-oils rather than the presence of catalysts during pyrolysis. Viscosity is influenced by the chemical makeup of the oil, including the profile of oxygenated compounds, the length of the chain, the oxidation product, and the level of unsaturation.

The kinematic viscosities of 4.00–4.30 centistokes (cSt) for the *Achyranthes aspera* bio-oils compare favourably with values reported in the literature for both bio-oils and biodiesels. Okekunle et al. (2021) reported viscosities of 28–33 mPa·s for catalytic pyrolysis bio-oils from Tectona grandis, which are substantially higher than the values obtained in the present study a difference attributable to the superior deoxygenation capacity of zeolite Y compared to MgO. Wada et al. (2025) reported a kinematic viscosity of 6.00 mm^2/s for Lannea microcarpa biodiesel, which is at the upper limit of the ASTM D6751 specification (1.9–6.0 mm^2/s) and slightly above the values obtained in the present study. Adeyemi et al. (2021) reported a viscosity of 4.2 mm^2/s for Sand Apple seed oil ethyl ester, which closely aligns with the values obtained in this study (4.00–4.30 cSt), confirming that tropical lignocellulosic feedstocks under catalytic conversion can produce bio-oils with near-diesel viscosity. Binhweel et al. (2021) further contextualise these values, reporting kinematic viscosities of 3.14–5.82 mm^2/s across eleven different biodiesel sources a range within which the *Achyranthes aspera* bio-oil values (4.00–4.30 cSt) comfortably sit. It is important to note that high viscosity in bio-oils is associated with incomplete atomisation, poor air-fuel mixing, and combustion deposits; the near-diesel viscosity achieved in this study therefore represents a significant quality advantage and is consistent with the upgrading effect of zeolite Y confirmed by Reza et al. (2023). To further contextualise these values against the broader bio-oil literature, non-catalytic pyrolysis bio-oils from various biomasses have been reported to exhibit viscosities ranging from 63 to 418 cP far exceeding crude petroleum oil at approximately 23 cP primarily due to lignin-derived high-molecular-weight hydrocarbons (Reza et al., 2023). By comparison, the dynamic viscosity of catalytically upgraded bio-oil from rape straw pyrolysis over nanocrystalline HZSM-5 was reported to be 5.12 mm^2/s, which falls within the diesel specification range closely comparable to the 4.00–4.30 cSt obtained in the present study (Reza et al., 2023). This demonstrates that zeolite Y

catalysis in the *Achyranthes aspera* system achieves a level of viscosity reduction consistent with the best-performing zeolite catalysts reported in the literature.

D.6. API Gravity

API gravity is a key measure of the density of petroleum liquids relative to water. According to Table 9, the API gravities of bio-oils produced from biomass pyrolysis at 400°C varied with biomass/catalyst ratios: 100/0 (40.00), 95/5 (45.18), 90/10 (45.50), and 85/15 (45.58). Similarly, at 500°C (Table 4.6), the API gravities for these ratios were 100/0 (40.00), 95/5 (45.09), 90/10 (45.10), and 85/15 (45.10). In comparison, diesel fuel typically has an API gravity around 45.0 - 46.0. The variations in API gravity with different biomass/catalyst ratios suggest that the introduction of zeolite Y catalysts during biomass pyrolysis can influence the density and composition of bio-oils. Higher catalyst ratios generally result in slightly higher API gravity values, indicating that catalysts may promote the production of bio-oils with lighter and more buoyant components.

The progressive increase in API gravity with catalyst loading (from 40.00 at 100/0 to 45.58 at 85/15 for 400°C) reflects the progressive reduction in bio-oil density as deoxygenation intensifies, and places the catalytic *Achyranthes aspera* bio-oil within the distillate fuel range (API gravity 35–50), which is directly comparable to petroleum diesel. The density-API gravity relationship is consistent with the findings of Binhweel et al. (2021), whose comparative review confirmed that biodiesel density at 15°C ranges from 867 to 889 kg/m^3 for vegetative oil sources, corresponding to API gravities broadly within the 24–35 range lower than the values obtained in the present study, further confirming that the *Achyranthes aspera* catalytic bio-oil is lighter and more petroleum-compatible than most biodiesels from transesterification routes. Wada et al. (2025) reported a density of 0.8965 g/cm^3 for Lannea microcarpa biodiesel, which corresponds to an API gravity of approximately 26.5 significantly lower than the 40–45.58 range obtained in the present study once again highlighting the superior upgrading achieved via zeolite Y catalysis in the *Achyranthes aspera* pyrolysis system. Chukwuneke et al. (2022) reported an API gravity of 19.29 for Swietenia macrophylla bio-oil substantially lower than the catalytic *Achyranthes aspera* bio-oil values of 40.00–45.58 which further highlights the significant fuel quality upgrading achieved through zeolite Y catalysis in the present study. A diesel-equivalent API gravity of approximately 35–40 is typical for gas oil, while gasoline ranges from 55–65; the catalytic *Achyranthes aspera* bio-oils falling in the 45–46 range place them in the distillate fuel category, indicating strong compatibility with existing engine and infrastructure systems. These API gravity values are therefore a strong indicator of the fuel's compatibility with conventional compression ignition engines and existing blending and distribution infrastructure.

E. Higher Heating Value Analysis

Table 10 exhibit the higher heating values (HHV) of the raw sample and the bio-oil. Equations were used to calculate the HHV of the biomass sample, bio-oil, and bio-oil based on the CHNSO elemental analysis. *Achyranthes aspera*'s HHV for raw biomass was calculated to be 20.76MJ/kg, respectively. *Achyranthes aspera* bio-oil had HHVs of 29.04, and 29.07 MJ/kg, respectively at 400℃, and 500℃. Based on the values provided, it appears that the catalytic pyrolysis of *Achyranthes aspera* at different biomass/catalyst ratios (b/c) resulted in higher heating values (HHV) compared to the raw sawdust samples.

At a b/c ratio of 95/5, the HHV of bio-oil for *Achyranthes aspera* were 30.56, and 30.91 MJ/kg, respectively at 400℃ and 500℃. At a b/c ratio of 90/10, the HHV of bio-oil for *Achyranthes aspera* were 32.14, and 32.43 MJ/kg, respectively at 400℃ and 500℃. At a b/c ratio of 85/15, the HHV of bio-oil for *Achyranthes aspera* were 32.07, and 32.80 MJ/kg, respectively at 400℃ and 500℃. Additionally, the summations of the heating values of the product yield at different biomass/catalyst ratios (b/c) were also higher than the heating value of the raw sawdust sample. For the sample, the heating value rose as the catalyst ratio rose. More so, the results shown that utilization of catalyst increases the higher heating value of bio-oil compared to the non-catalyzed bio-oil which is consistent with the findings of Campusano et al. (2024). Increased catalytic ratio promotes higher aromatic hydrocarbon production, lower oxygen

content, higher heating value, and improved bio-fuel stability for combustion applications. These HHV values compare favourably with findings from related studies. Okekunle et al. (2021) reported HHVs of 40.31–42.08 MJ/kg for catalytic pyrolysis bio-oils from Tectona grandis using MgO catalyst higher than the values in the present study, which may be attributed to the higher carbon content (80–81 wt.%) of the Tectona grandis bio-oils compared to the *Achyranthes aspera* bio-oils. However, Okekunle et al. (2021) also reported non-catalytic bio-oil HHVs of only 36.47–36.76 MJ/kg, confirming that catalysis consistently elevates HHV across different feedstocks. Adeyemi et al. (2021) reported a heating value of 42.61 MJ/kg for Sand Apple ethyl ester, which is higher than the *Achyranthes aspera* catalytic bio-oil values, largely because transesterification-derived biodiesels retain more hydrocarbon chain integrity than pyrolysis bio-oils. Wada et al. (2025) reported a calorific value of 38.5 MJ/kg for Lannea microcarpa biodiesel higher than the non-catalytic *Achyranthes aspera* bio-oil (29.04–29.07 MJ/kg) but lower than the catalytic values achieved at the 85/15 ratio (up to 32.80 MJ/kg at 500°C). The progressive improvement in HHV with increasing zeolite Y loading in the present study thus confirms the catalyst's role in systematically improving the energy content of *Achyranthes aspera* bio-oil toward values competitive with established biofuel feedstocks. More broadly, the literature consistently confirms that bio-oil from fast pyrolysis has a typical HHV of 15–25 MJ/kg, compared with 42–46 MJ/kg for fossil fuels, reflecting the oxygen burden of raw pyrolysis bio-oil (Reza et al., 2023). The non-catalytic *Achyranthes aspera* bio-oil HHVs of 29.04–29.07 MJ/kg already exceed this typical raw bio-oil range, suggesting that the feedstock's lignocellulosic composition is inherently favourable for energy content. Furthermore, for zeolite-catalysed systems specifically, cobalt-based zeolite catalysis of Azolla and Ulva biomasses has been reported to raise HHV from 28.6 MJ/kg to 33.2 MJ/kg for Azolla and from 30.7 MJ/kg to 32.26 MJ/kg for Ulva (Reza et al., 2023). The catalytic HHV values obtained in the present study (30.56–32.80 MJ/kg) fall within and are closely aligned with these reported ranges, providing strong cross-study validation of the energy density improvements achieved through zeolite Y catalysis on *Achyranthes aspera* wood residue. The underlying mechanism is well established: zeolite catalysts facilitate cleavage of C–O and C–C bonds in pyrolysis vapours, converting oxygenated intermediates into lighter aromatic hydrocarbons with reduced oxygen content and elevated calorific value (Reza et al., 2023), consistent with the trend of increasing HHV with catalyst loading observed in this study.

Table 10. Higher Heating Value Analysis of the Bio-Oil.

		Temperature, 400°C				Temperature, 500°C			
	Raw Biomass	100/0	95/5	90/10	85/15	100/0	95/5	90/10	85/15
HHV (MJ/kg)	20.76	29.04	30.56	32.14	32.07	29.07	30.91	32.43	32.80

F. Novelty and Distinction from Existing Literature

The present study offers several distinctive contributions that differentiate it from prior work on bio-oil production and characterization. Most fundamentally, no previously published study has reported the physicochemical and fuel properties of bio-oil derived from *Achyranthes aspera* wood residue, making this work the first systematic investigation of this abundant tropical lignocellulosic biomass as a pyrolytic bio-oil feedstock. Studies on comparable woody biomasses, such as Gmelina arborea (Adegoke et al., 2021) and Swietenia macrophylla (Chukwuneke et al., 2022), have reported bio-oil densities of 1.02–1.13 g/cm^3 and kinematic viscosities of 14.0–24.5 cSt, along with acidic pH values of 3.11–3.93 properties that differ fundamentally from those obtained in the present study. The *Achyranthes aspera* bio-oil produced under zeolite Y catalysis exhibited significantly lower density (0.78–0.85 g/mL), near-diesel viscosity (4.00–4.30 cSt), and a markedly higher pH (7.50–8.50), demonstrating that feedstock selection and catalytic upgrading together produce a substantially different product profile than that of non-catalytic woody biomass pyrolysis.

Beyond the novelty of the feedstock, the study is distinguished by its application of zeolite Y as the upgrading catalyst. Zeolite-catalyzed pyrolysis of biomass has been explored for various feedstocks (Reza et al., 2023; Campusano et al., 2024), but the specific interaction of zeolite Y with *Achyranthes aspera* lignocellulosic structure characterized by the distinct tropical composition of this weed species has not previously been reported. The results demonstrate that zeolite Y exerts a strong deoxygenating effect on Achyranthes aspera volatiles, progressively raising bio-oil pH from 7.50 (non-catalytic) to 8.50 (85/15 ratio), reducing viscosity, increasing API gravity to near-diesel levels (45.58), and raising HHV from 29.04 MJ/kg (non-catalytic) to 32.80 MJ/kg (catalytic at 500°C, 85/15). This HHV improvement is consistent with catalytic pyrolysis literature reporting HHV gains from approximately 28–31 MJ/kg in non-catalytic conditions to 32–34 MJ/kg in zeolite-catalyzed systems (Campusano et al., 2024), but has not previously been demonstrated for this specific feedstock.

The study also advances the field methodologically by applying a desirability function optimization framework to Achyranthes aspera pyrolysis, which simultaneously evaluated the competing objectives of maximizing bio-oil yield while minimizing biochar and syngas formation. This multi-response optimization approach identified 95/5 biomass-to-catalyst ratio at 500°C as the optimal condition; a finding not previously established for this feedstock or through this approach. Furthermore, unlike several comparable studies that relied on a single temperature or non-standardized property measurements, the present study evaluated two temperatures (400°C and 500°C), four catalyst ratios, and seven ASTM-standardized fuel properties, providing a comprehensive and replicable reference dataset that did not previously exist for *Achyranthes aspera* bio-oil. In this regard, the present study fills a critical gap in the bioenergy literature, providing essential baseline data for future research on scale-up, catalyst regeneration, blending, and techno-economic assessment of *Achyranthes aspera* -based biofuel systems.

Beyond the novelty of the feedstock itself, this study advances the field in three additional dimensions. First, it is the first to evaluate the effect of zeolite Y catalyst loading on the product yield distribution and fuel property optimization of *Achyranthes aspera* -derived bio-oil, providing evidence that a moderate biomass-to-catalyst ratio of 95/5 at 500 °C represents an optimal condition yielding 52.95 wt.% bio-oil with near-diesel fuel properties. Second, the study applies a desirability function optimization approach to simultaneously maximize bio-oil yield while minimizing biochar and syngas formation a multi-response optimization framework not previously applied to this feedstock. Third, this work generates the first systematic database of ASTM-standardized fuel properties (flash point, pour point, pH, density, kinematic viscosity, API gravity, and HHV) for *Achyranthes aspera* bio-oil under both non-catalytic and catalytic conditions, providing a benchmark for future research and enabling direct comparison with both conventional petroleum fuels and other biomass-derived oils. Collectively, these contributions address a clear gap in the bioenergy literature and support the potential integration of *Achyranthes aspera* wood residue into renewable fuel systems.

IV. CONCLUSION

This study investigated the catalytic pyrolysis of Achyranthes aspera wood residue using zeolite Y to produce bio-oil with improved physicochemical and fuel properties. The results demonstrated that both temperature and biomass-to-catalyst ratio significantly influenced product yield distribution and liquid fuel quality, although these statistical findings should be interpreted with caution given the single observation per treatment combination and use of the interaction term as a proxy error term. The highest bio-oil yield was obtained at a reaction temperature of 500 °C and a biomass-to-catalyst ratio of 95/5, representing the optimal condition for maximizing liquid fuel production while minimizing char and gas formation.

Statistical and optimization analyses confirmed that moderate catalyst loading promotes effective thermal decomposition and catalytic cracking, enhancing the formation of condensable volatiles and improving overall process efficiency. The desirability function approach provided a systematic means of

identifying the optimal reaction condition, confirming that process variables can be fine-tuned to achieve high-quality bio-oil output.

The produced bio-oil exhibited favorable fuel properties, including moderate viscosity, acceptable density, reasonable heating value, and satisfactory flash and pour points. Although slightly acidic due to oxygenated species, these properties indicate strong potential for upgrading and blending with conventional petroleum fuels.

Overall, the findings establish Achyranthes aspera wood residue as a promising renewable feedstock for sustainable bio-oil production. Future research should focus on catalyst regeneration, upgrading of the produced oil to reduce acidity and improve stability, and techno-economic assessment of large-scale conversion systems to advance the commercial viability of this process. More so, a recommendation for fully replicated experimental designs in future studies on Achyranthes aspera pyrolysis, to enable rigorous ANOVA, uncertainty quantification, and reproducibility verification.

DECLARATIONS

Acknowledgements: We hereby acknowledge the entire management staff of Bells University of Technology, Ota, Nigeria for creating enabling environment to carry out this research.

Author's Contributions: Conceptualization, J.A..; methodology J.A.. and K.L.; validation, K.L.; investigation, A.C., I.A., and O.O.; resources, A.C., I.A., and O.O.; data curation, K.L.; writing-original draft preparation, A.C., I.A., and O.O.; writing-review and editing, K.L..; supervision, J.A. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Disclosure: The authors declare no conflict of interest.

Copyright Statement: The authors own the copyright of their work published in the journal and their work is published under the CC BY-NC 4.0 license.

Supporting/Supporting Organizations: This research received no external funding.

Ethical Approval and Participant Consent: This article does not contain any studies with human or animal subjects. It is declared that during the preparation process of this study, scientific and ethical principles were followed and all the studies benefited from are stated in the bibliography.

Plagiarism Statement: This article was checked by the plagiarism program. No plagiarism detected.

Availability of Data and Materials: Data sharing not applicable.

Use of AI Tools: The authors declare that Artificial Intelligence (AI) tools were used to assist in language editing and improving the clarity of the manuscript. All scientific content, interpretations, and conclusions are entirely the responsibility of the authors. The authors further affirm full responsibility for the originality, accuracy, and integrity of the work.

REFERENCES

Adegoke I.D., Ogunsanwo O.Y., Ige A.R. (2021). Bio-Fuel Properties and Elemental Analysis of Bio-Oil Produced from Pyrolysis of Gmelina Arborea. Acta Chemica Malaysia (ACMY) 5(1): 38-41. https://doi.org/10.2478/acmy-2021-0006

Adeyemi D.T., Saleh A., Akande F.B., Oniya O.O., Ola F.A. (2021). Determination of Fuel Properties of Biodiesel from Sand Apple Seed Oil with Automative Gas Oil Blend. Journal of Applied Science, Environmental and Management 25 (8): 1365-1369. https://doi.org/10.4314/jasem.v25i8.12

Ameh, V.I., Ayeleru, O.O, Nomngongo, P.N., Ramatsa, I.M. (2024). Bio-oil production from waste plant seeds biomass as pyrolytic lignocellulosic feedstock and its improvement for energy potential: A review. *Waste Management Bulletin,* 2 (2): 32-48. https://doi.org/10.1016/j.wmb.2024.03.002

Asfaw M.D., Yadeta A.T., Yewalie B.G., Negash Y.W. (2025). Production and Characterization of Biodiesel from *Argemone Mexicana* Seed Oil. Results in Chemistry 13: 102055. https://doi.org/10.1016/j.rechem.2025.102055

ASTM D445-24. (2024). Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity). ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D0445-24

ASTM D2270-24. (2024). Standard Practice for Calculating Viscosity Index from Kinematic Viscosity at 40 °C and 100 °C. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D2270-24

ASTM D792-20. (2020). Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D0792-20

ASTM D4052-22. (2022). Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D4052-22

ASTM D93-20. (2020). Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D0093-20

ASTM D97-17b. (2017). Standard Test Method for Pour Point of Petroleum Products. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D0097-17B

ASTM D2500-23. (2023). Standard Test Method for Cloud Point of Petroleum Products and Liquid Fuels. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D2500-23

ASTM D7946-19. (2019). Standard Practice for Initial Calibration and Performance Qualification of Inductively Coupled Plasma — Optical Emission Spectrometers. ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D7946-19 https://doi.org/10.2478/acmy-2021-0006

Budiman, S.A., and Mulyono, R.P. (2018). Silica-Alumina Based Catalytic Cracking of Bio-Oil Using Double Series Reactor. *International Journal of Renewable Energy Research*, 8 (1): 414-420.

Binhweel, F., Bahadi, M., Pyar, H., Alsaedi, A., Hossain, M.S., and Ahmad, M.I. (2021). A Comparative Review of Some Physicochemical Properties of Biodiesels Synthesized from Different Generations of Vegetative Oils. *Journal of Physics: Conference Series*, 1900 (2021) 012009. https://doi.org/10.1088/1742-6596/1900/1/012009

Cai, N., Zhang, H., Nie, J., Deng, Y., and Baeyens, J. (2020). Biochar from Biomass Slow Pyrolysis. *IOP Conference Series: Earth and Environmental Science,* 586: 1-34. https://doi.org/10.1088/1755-1315/586/1/012001.

Campusano, B., Jabbour, M., Abdelouahed, L., Mignot, M., Devouge-Boyer, C., and Taouk, B. (2024). Improvement of Properties of Bio-Oil from Biomass Pyrolysis in Auger Reactor Coupled to Fluidized Catalytic Bed Reactor. *Processes,* 12 (11): 1-23. https://doi.org/10.3390/pr12112368

Camur H. and Alassi E. (2021). Physicochemical Properties Enhancement of Biodiesel Synthesis from Various Feedstocks of Waste/Residential Vegetable Oils and Palm Oil. Energies 14: 4928. https://doi.org/10.3390/en14164928

Chiaberge, S., Leonardis, I., Fiorani, T., Cesti, P., Reale, S., and Angelis, F.D. (2014). Bio-Oil from Waste: A Comprehensive Analytical Study by Soft-Ionization FTICR Mass Spectrometry. *Energy Fuels,* 28 (3): 2019–2026. https://doi.org/10.1021/ef402452f

Chukwuneke, J. L., Umeji, A. C., Sinebe, J. E., and Fakiyesi, O. B. (2020). Optimization of composition of selected biomass for briquette production. *Universal Journal of Mechanical Engineering*, 8(4): 227–236. https://doi:10.13189/ujme.2020.080408

Chukwuneke, J. L., Sinebe, J. E., Orugba, H. O., Olisakwe, H. C., and Ajike, C. (2022). Production and physico-chemical characteristics of pyrolyzed bio-oil derived from cow hooves. *Arab Journal of Basic and Applied Sciences,* 29(1): 363–371. https://doi.org/10.1080/25765299.2022.2129633

Hu, X., and Gholizadeh, M. (2020). "Progress of the Applications of Bio-Oil," *Renewable and Sustainable Energy Reviews*, 134, p. 1-20, 2020. https://doi.org/10.1016/j.rser.2020.110124

Imam T. and Capareda S. (2012). Characterization of Bio-oil, Syn-gas and Bio-char from Switchgrass Pyrolysis at Various Temperatures. *Journal of Analytical and Applied Pyrolysis,* 93: 170-177. https://doi.org/10.1016/j.jaap.2011.11.010

Jamilatun S., Elisthatiana Y., Aini S.N., Mufandi I., Budiman A. (2020). Effect of Temperature on Yield Product and Characteristics of Bio-oil from Pyrolysis of Spirulina platensis Residue. *Journal of Islamic Science and Technology,* 6 (1): 1-13.

Kaoje, H., Adeleke, A., Anosike-Francis, E., Jesuloluwa, S., Ogedengbe, T., Rasheed, H., Okolie, J. (2025). Transforming Sawdust Waste into Renewable Energy Resources: A Comprehensive Review on Sustainable Bio-Oil and Biochar Production via Thermochemical Processes. *Journal of Renewable Material,* 1-57. https://doi.org/10.32604/jrm2025020250109

Kassem, Y., Aktug, B., Ozgenc, E., Dib, M.S., Ghisheer, M.M.M., Cole, O.A., and Camur H. (2018). Effect of Storage Period on Kinematic Viscosity and Density of Biodiesel and its Blends with Ultra-low-sulfur Diesel Fuel at Constant Storage Temperature. *International Journal of Smart Grid and Clean Energy,* 7 (2): 130-144. https://doi.org/10.12720/SGCE.7.2.130-144.

Makavana J.M., Sarsavadia P.N., and Chauhan P.M. (2020). Effect of Pyrolysis Temperature and Residence Time on Bio-char Obtained from Pyrolysis of Shredded Cotton Stal. *International Research Journal of Pure and Applied Chemistry,* 21(13): 10-28. https://doi.org/10.9734/IRJPAC/2020/v21i1330236.

Maulinda, L., Husin, H., Arahman, N., Rosnelly, C.M., Syukri, M., and Nasution F. (2023a). The Influence of Pyrolysis Time and Temperature on the Composition and Properties of Bio-Oil Prepared from Tanjong Leaves (Mimusops elengi). *Sustainability,* 15(18): 1-17. https://doi.org/10.3390/su151813851

Maulinda, L., Husin, H., Rahman, N.A., Rosnelly, C.M., Nasution, F. Abidin, N.Z., Yani, F.T. (2023b). Effects of Temperature and Times on the Product Distribution of Bio-oils Derived from Typha Latifolia Pyrolysis as Renewable Energy. *Results in Engineering,* 18: 1-11. https://doi.org/10.1016/j.rineng.2023.101163

Montgomery D.C. (2017). Design and Analysis of Experimental (9th ed.). John Wiley and Sons, Inc., River Street, Hoboken, New Jersery, USA, 640 p.

Nanda, S., Mohammad, J., Reddy, S.N. and Kozinski J.A. (2014). Pathways of Lignocellulosic Biomass Conversion to Renewable Fuels. Biomass Conversion Biorefinery, 4: 157-191. https://doi.org/10.1007/s13399-013-0097-z

NFPA 30. (2021). Flammable and Combustible Liquids Code. National Fire Protection Association, Quincy, MA, USA 160 p.

Nigam, P. (2023). A Review Analysis on Different Renewable Energy Sources. International Journal of Emerging and Scientific Technologies (IJESTECH) 1 (1): 5-10.

Pinto, L.F., Silva, D.I.S., Silva, F.R., Santos, B., Soletti, J.I., and Carvalho, S.H. (2012). Assessment of the Feasilibility of different Oil Sources to Biodiesel. *Acta Scientiarum*, 34 (2): 227-231.

Putun, E. (2010). Catalytic Pyrolysis of Biomass: Effects of Pyrolysis Temperature, Sweeping Gas Flow Rate and MgO Catalyst. *Energy,* 35 (7): 2761-2766. https://doi.org/10.1016/j.energy.2010.02.024

Oasmaa, A., Kalli, A., Lindfors, C., Elliott, D.C., Springer, D., Peacocke, C., and Chiaramonti, D. (2012). Guidelines for Transportation, Handling, and Use of Fast Pyrolysis Bio-oil: 1. Flammability and Toxicity. Energy and Fuels, 26 (6): 3864-3873. https://doi.org/10.1021/ef300418d

Okekunle, P.O., Ogunsola, A.D., Babayemi, O.A., Abodunrin, E.D., and Daramola, O.M. (2021). Analysis and Comparison of the Fuel Properties of Bio-Oils Produced by Catalytic Fast Pyrolysis of *Tectona grandis*. *Uludag University Journal of The Faculty of Engineering*, 26(2): 693–705. https://doi.org/10.4025/actasctechnol.v34i211259

Osanyinpeju, K.L., Aderinlewo, A.A., Adetunji, O.R., and Ajisegiri, E.S.A. (2018a). Performance Evaluation of Mono-Crystalline Photovoltaic Panels in FUNAAB, Alabata, Ogun State, Nigeria Weather Condition. *International Journal of Innovations in Engineering Research and Technology*, 5 (2): 8-20. https://doi.org/10.5281/zenodo.5804833

Osanyinpeju, K.L., Aderinlewo, A.A., Adetunji, O.R., and Ajisegiri, E.S.A. (2018b). Development of a Solar Powered Poultry Egg Incubator for South West Nigeria. *International Journal of Innovative Research and Creative Technology*, 3 (6): 50-63. https://doi.org/10.5281/zenodo.5794733

Osanyinpeju, K.L., Aderinlewo, A.A., Adetunji, O.R., Ajisegiri, E.S.A. (2018c). Performance Evaluation of Mono-Crystalline Photovoltaic Panels in Funaab, Alabata, Ogun State, Nigeria Weather. *International Journal of Innovations in Engineering Research and Technology,* 5 (2): 1-14.

Osanyinpeju, K.L., Aderinlewo, A.A., Adetunji, O.R., Ajisegiri, E.S.A. (2018d). Output Power and Voltage-Time Characteristics of Mono-Crystalline Photovoltaic Panel at Federal University of Agriculture, Abeokuta (FUNAAB), Alabata, OgunState, Nigeria Under FUNAAB Weather Condition. *International Journal of Advanced Engineering Research and Applications (IJAERA),* 3 (2): 349-360.

Oyebanji, J. A., Obinna, J. P., and Oyebanji, O. T. (2023). Characterization of *Terminalia ivorensis* bio-char produced using a fixed-bed tubular reactor. *International Journal of Renewable Energy Technology*, 14 (2): 115-125.

Oyebanji, J.A., Okekunle, P.O., Lasode, O. A. and Oyedepo, S.O. (2018). Chemical Composition of Bio-oils Produced by Fast Pyrolysis of Two Energy Biomass. *Biofuels,* 9 (4): 479-487.

Reza, M.S., Iskakova, Z.B., Bekmyrza, K.Z., Kubenova, M.M., Bakar, M.S.A., Azad, A.K., Roy, H., Islam, M.S. (2023). Influence of Catalyst on the Yield and Quality of Bio-Oil for the Catalytic Pyrolysis of Biomass: A comprehensive Review. *Energies*, 16: 1-39.

Rohim, R., Ahmad, R., Ibrahim, N. (2014). Effect of Pyrolysis Parameter and Catalyst on Oil Production from Empty Fruit Bunch. 8th MUCET 2014, 10-11 November, Malaysia 4pp, 2014.

Russo, D., Portarapillo, M., and Benedetto, A.D. (2023). Flash Point of Biodiesel/Glycerol/Alcohol Mixtures for Safe Processing and Storage. *Journal of Loss Prevention in the Process Industries* 83: 1-7.

Santoso, R., Hendragiri, D., and Garniwa, I. (2022). Biomass Value Improvement and Economic Analytics in Power Plant. *E3S Web of Conferences,* 35: 1-6. https://doi.org/10.1051/e3sconf/202235901008

Selvaraj, M., Sriramajayam, S., Ramesh, D., and Karthikeyan, S. (2020). Performance Evaluation of Diesel Engine using Fuel Oil Produced from Plastic Waste. *International Journal of Current Microbiology and Applied Sciences*, 9 (10): 17-23. https://doi.org/10.20546/ijcmas.2020.910.003

Stelmach, S., Ignasiak, K., Czardybon, A., Bigda, J. (2023). Evaluation of Bio-Oils in Terms of Fuel Properties. *Processes,* 11:1-12. https://doi.org/10.3390/pr11123317

Wada I., Yahaya D.B. and Garba I. (2025). Physico-Chemical Properties of Biodiesel Derived from Lannea Microcapa Oil: A Comparative Analysis with Fossil Diesel. FUDMA Journal of Sciences (FJS), 9 (2): 209-215. https://doi.org/10.33003/fjs-2025-0902-3164

Yusof, H., Tamaldin, N., Abdollah, M.F.B., and Khalid, A. (2025). Evaluation of the Storage Effect on the Fuel Properites for Variety Biodiesel Blends. *ARPN Journal of Engineering and Applied Sciences* 10 (17): 7707-7711.